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Separation of Plastic Waste from Mixed Waste: Existing and Emerging Sorting Technologies Performance and Possibilities of Increased Recycling Rate with Finland as Case Study

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ABSTRACT

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Keywords: Sustainable waste management; automated sorting; mixed waste processing facility; plastic recovery facility; mechanical biological treatment; residual waste treatment facility; separation technology; separation process; residual waste; recycling rate

The current world view of the production, usage and disposal of plastics, especially flexible plastic packaging, is that of a tale that has generated several environmental and sustainability issues. In excess of 7% of world fossil, a non-renewable resource, is used as feedstock and energy for the production of plastics. Over 250 kt of waste plastics may already be floating and contaminating the world's seas leading to the death of thousands of marine life and other animals; with an estimated 10% microplastics capable of finding their way into the food chain.

The ever-increasing demand for plastics products, is liable to significantly increase these figures in the not too distant future. However, advances in technologies and systems for the collection, identification, sorting, separation and reprocessing of recyclable plastics are providing new prospects for recycling to closing the loop. Recycling provides opportunities to reduce oil, gas and coal usage; greenhouse gas emissions; the unleashing of plastics debris into the oceans and other water bodies; and the quantities, by volume and weight, of waste requiring disposal.

Challenges involved in the collection, separation and sorting systems of plastic wastes have effectively limited it recycling rate and consequently made it arguably the least recycled waste stream; yet it is the most plentiful (i.e. by volume) of post-consumer wastes. In recent years, automated sorting has influenced and changed the way plastic wastes are segregated from other waste fractions and contaminants. This study examined how emerging and existing automated separation technologies performance could help impact and further improve the recycling process and caused corresponding significant increase in recycling rate.

With Finland as case study, the focus was on the collection and utilization of mixed residual waste from municipal solid waste; and how processing this stream using separation technologies with high performance could help increase the recycling rate of plastics fraction (i.e. polymers) present in the stream.

Ensuing case results suggested that with a source separation efficiency of 40-60%, it is possible to recover for recycling nearly half (i.e. 48%) of the total plastic packaging present in the mixed residual waste. This further increased plastic packaging recycling rate by 29. In this wise, it made about 102000 additional tonnes of plastic packaging available for recycling. Total plastic waste amount in the residual waste was found to be 16.8% of the total mixed residual waste. The derived recycling rate of 29% for plastic packaging corresponded to total plastics recycling rate of 24% with prospect for further possible increase.

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LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ACC	American Chemistry Council
AD	Anaerobic Digestion
ADC	Alternative Daily Cover (Backfilling)
ADEME	French Agency for Environment and Energy Management
BFR	Brominated Flame Retardant
CaCl2	Calcium Chloride
C&D	Construction and Demolition
CIWEM	Chartered Institute of Water and Environmental Management
DEFRA	Department for the Environment, Food and Rural Affairs
EC	European Commission
ELV	End of Life Vehicle
EPA	United States Environmental protection Agency
EPS	Expanded Polystyrene
EVOH	Ethylene vinyl alcohol
EU	European Union
GBB	Gershman, Brickner & Bratton, Inc.
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
HIPS	High impact polystyrene

JRC	Joint Research Centre
KPI	Key Performance Indicator
Kt	Kilo tonne (Thousands of tonnes)
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
LIBS	Laser-Induce Breakdown Spectroscopy
LIPS	Laser-Induce Plasma Spectroscopy
LoT	Landfill only Target
LUT	Lappeenranta University of Technology
MFA	Mass Flow Analysis
MDS	Magnetic Density Separation
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
Mt	Mega tonne (Million tonnes)
MWPF	Mixed Waste Processing Facility
NEA	National Environmental Agency
NIR	Near Infrared
OECD	Organization for Economic Co-operation and Development
OEE	Overall Equipment Effectiveness
PA	Polyamide
PBDE	Polybrominated Diphenyl Ethers
PE	Polyethylene
PET	Polyethylene Terephthalate
POPs	Persistent Organic Pollutants
PP	Polypropylene
PPWD	Packaging & Packaging Waste Directive
PS	Polystyrene
PUR	Polyurethane

PVC	Polyvinyl Chloride
RIC	Resin Identification Code
RDF	Refuse Derived Fuel
RWTF	Residual Waste Treatment Facility
WFD	Waste Framework Directive
WRAP	Waste & Resources Action Programme
WTE	Waste to Energy
WTR	Waste to Resources

LIST OF SYMBOLS

%	Percent
>	Greater than
<	Less than
=	Equal to
≈	Approximation

1. INTRODUCTION

1.1. Introduction

Waste separation technology is the main backbone of any material recycling and or recovery facility process. This implies that a failed separation operation will automatically translate into a failed recycling/recovery process. This, immediately, will be evident in the poor yield, quality and or purity levels of recycled products that will be produced. Separation of plastics waste from mixed waste stream, such as packaging waste, waste electrical electronic equipment (WEEE), end-of-life (ELV) represent major problems in the waste management industry.

Waste plastics separation technologies are significant but are often neglected when passing legislative laws on recycling of plastics waste. For example, the EU strategy on plastic waste resolution 2014, has failed to address and rollout binding targets for the collection, sorting and recycling, as well as mandatory criteria for plastics recyclability (European Commission, 2013). Packaging and Packaging Waste Directive (PPWD), Waste Framework Directive (WFD) and landfill ban Directive have not been able to address these issues either.

In other scenarios, waste plastics separation technologies are often overlooked and treated as mere part of recycling technologies. These facts are evident as we observed the absence of separate waste bins or bags for plastic wastes in our homes and municipalities; and the nonexistence of official statistical data for total plastics waste even in most EU member countries.

Notwithstanding, plastics from mixed waste streams poses unique challenges not only to the biotic and abiotic elements in the ecosystem but as well as for both existing and current plastics separation technologies. These challenges may have been ascribed to the presence of additives such as dopants and retardants in plastics; dark plastics; opaque plastics; foil/flexible plastics; cross-contamination and presence of other contaminants such as fluids and organic substances with regards to the latter case. And for the former, the lack of right policy, economic incentives and subsidies, key stakeholders' participation and technological shortcoming have been observed to be responsible for the environmental mishaps.

1.2. Importance of the Issue on a Global and Local Scale

The consequence of lack of legislative actions, neglect and failure to recognize and re-evaluate the importance of plastic waste separation technologies will perpetually keep plastic packaging waste recycling rate in the EU below 50% rate. Given the fact that EU is currently the global leader in recycling, this percentage figure is significantly less in other countries of the world. Per recent study carried out by the Denkstatt Group, the optimum level for plastic packaging recycling rate, using today's technology as well as the current calculation methods, lies somewhere between 35% and 50%, depending on the country's collection, sorting and recycling capabilities (Bourguignon, 2016). Despite this study, EU has set a new 2025 recycling and preparation for reuse rate of 55% for plastic packaging waste; this, many have concluded as unrealistic and over ambitious especially since the average plastic packaging recycling rate in Europe was reported as being under 40% in 2014 (Bourguignon, 2016).

From the perspective of waste management hierarchy, when less than 50% of plastic packaging wastes had been recycled, the remaining greater part are sent to incineration plants and landfills; some finds their way into waterways and oceans. Meanwhile, 42% of EU plastic waste is still being landfilled (European Commission, 2014) and much more in the world over. This potentially increases the volume and piles of non-biodegradables which have multiple ripple effects such as blockage of drainage systems, possible leaching of underground waters, release of toxic gases; killing of marine life, seabirds and other animals when eaten as food; and dampening of the atmospheric air causing pollution and visibility issues when plastic wastes are burnt in open fields. All of which are detrimental to the human health, economy (Blue Economy inclusive and severely impacted), property, environment and welfare.

Another dimension to this problem could be seen in the plastic waste global recycling markets with increasing demand for high quality (well sorted) imports, of which China plays a major role as the largest importer, and Europe, collectively happens to be the major exporter. Globally traded secondary plastics alone was projected by Pöyry to hit 49 Mt in 2015. The decision of the Chinese Government to increase preference for single (or well sorted) polymers with less contamination through it Green Fence operation which kicked off in 2013, is most likely to impact negatively on the quantity (both by volume and weight) level of exports from the exporting countries (Velis, 2014).

Yet another worrying-some dimension worth observing is the fact that over 250 kt of waste plastics may already be floating and contaminating the world's seas; with an estimated 10% microplastics capable of finding their way into the food chain. This figure is expected to increase consistently when unchecked, especially given the fact that in 2015 alone, more than 322 Mt of plastics was produced globally, and this production rate is expected to double by 2050 (SYKE, 2017).

These implications underscore the need for an effective and efficient separation and recycling of plastic wastes from mixed waste streams for high valued quality and purity recycled products. Obviously, waste management needs clear guidance to perform efficiently and waste packages directives need more input from institutions and stakeholders if a true Circular Economy society is to emerge with its attendant potential opportunities (Bourguignon, 2015).

Well sorted plastic wastes are fit and good for reuse and recycling. This way, plastics materials are held in perpetual loop, thus shielding the environment from its daring and multiple negative impacts. The global oil industry and plastics industry could save huge amount in cost, annually. According to a study, the accumulation of these savings could potentially result into 50% cost saving in one to two decades. Dependence and reliance on virgin plastics could be reduced, thus conserving petroleum, a non-renewable energy source, and saving it from depletion.

Globally, approximately 4% of oil and gas, non-renewable resources, could be saved as feedstock for virgin plastics production and a further 3-4% expended on energy for their manufacture (Hopewell et. al., 2009). Oceans and marine bodies could be free of plastics debris thereby preventing most marine life and wildlife from extinction and dying in their numbers. Poisonous gases and greenhouse gases could be prevented from being release into the atmosphere through effective and environmental friendly plastics separation and recycling techniques. Incineration of plastics waste as fuel will become less and less preferred and problematic to the environment.

Against the backdrop of the ever-increasing volume of plastics production and consumption necessitated by growing demand by consumers, it is extremely important to develop technological systems to avoid and prevent post-consumer plastic wastes ending up in landfills or in being incinerated in an uncontrolled environment. The problems of plastic

wastes can be traced to local sources which have global dimension, as our oceans and seas; and atmosphere known no border or global boundaries. Therefore, these issues as it stands, remain local issues needing global attention. The significance of this would be evident in the economy, environment, and social life of the individual and the nations if specific concerted effort can be taken to develop and support the recycling process and its associated separation/sortation technologies to make them economically feasible and viable.

1.3. Concise Objectives of the Study

Aside the main objectives, this report is also aimed at raising awareness on the significance of waste plastic separation technologies performance in tackling the multifaceted issues which plastic wastes have come to constitute. This knowledge appears low at the moment, even amongst seemly advanced and civilized societies and probably non-existing in developing and emerging economies.

The main objectives of this study is directed at seeking to address the following research questions:

- What are the challenges and or difficulties that has made mixed plastic waste from household and other municipal solid waste sources the least recycled packaging waste fraction?
- How has or can separation technologies performance help resolve the above-mentioned issues and elicit an increase in the recycling rate of plastic packaging and total plastics in general?
- Is it possible to recycle at quality level at par with virgin plastics for economic, the environment, and social reasons; what are the recommendations and suggestions?

Consequently, his study seeks to identify the challenges that has made plastic waste fraction the least recycled amongst other recyclable waste fractions with an overarching objective to demonstrate possibilities for increased plastics recycling rate from different scenarios, utilizing mixed MSW and or mixed residual wastes; based primarily on existing and emerging separation technologies performance.

At the end, useful recommendations and suggestions will be made to encourage further improvement not just in the purity level for some plastic recyclate types which already stands at about 99.9%, but also to suggest possibilities to increase recycling rates and the quality of all final plastic recyclate products to a level at par with virgin plastics. And also, to drum up

legislative support for the recycling of plastics; provision of economic incentives and subsidies where necessary such as in the acquisition of emerging sorting equipment and or machineries, to encourage plastics recycling and seeking social participation of key stakeholders.

2. A PREVIEW ON PLASTIC WASTES

2.1. Plastic Waste Types, Properties and Uses

Most post-consumer mixed MSW and unsorted household waste are known to contain a wide range of plastic polymer types, identifiable by their resin content label, from which they are produced. This label is referred to as RIC (Resin Identification Code) and it represents the recyclability preference for each polymer. It is symbolized by a number (depicting preference, with 1 being the most preferred) and three "chasing arrows."

In recent years, these arrows have been replaced by a solid triangle in the 2013 revision of the code by ASTM International, a body that took over the coding system administration from SPI (Society of the Plastics Industry) in 2008. This was done in response to consumers' and other stakeholders' confusion with regards to the recyclability of some plastic waste material, stressing that the presence or absence of a Code on a plastic product does not indicate whether it is recyclable or not. Nonetheless, the primary purpose of the codes is for efficient separation/sorting of different polymer types for recycling (ASTM, 2014; Villanueva & Eder, 2014). Tables 1 depicts the different plastic polymer types, their properties and uses. Table 2 shows the new RIC symbols.

2.1.1 Plastic Waste Fraction Composition

The major plastic polymers predominantly found in household waste and other MSW sources are Polyethylene (PE) (Linear Low Density PE, Low Density PE and High Density PE), Polyethylene Terephthalate (PET), Polypropylene (PP), Polystyrene (PS), and Polyvinyl Chloride (PVC). These also are the most consumed in large quantity whose shares may vary slightly as influenced by the collection efficiency of the different plastic products, and their different lifespan (Villanueva & Eder, 2014). Polyethylene (i.e. LLDPE, LDPE, and HDPE) are overall the most abundant polymers in waste plastics due to their dominance in packaging applications, accounting for more than half the total plastic waste. Figure 1 represents post-consumer plastic waste by polymers in EU27 plus Norway and Switzerland in 2010 from a total of 24.713 kt.

Apparently, polyolefin (i.e. PEs and PP) represents approximately 60% of the total plastic waste generation in MSW either from households or other MSW sources. Taken together with PET and PVC they represent 80% of the total plastic waste generation.

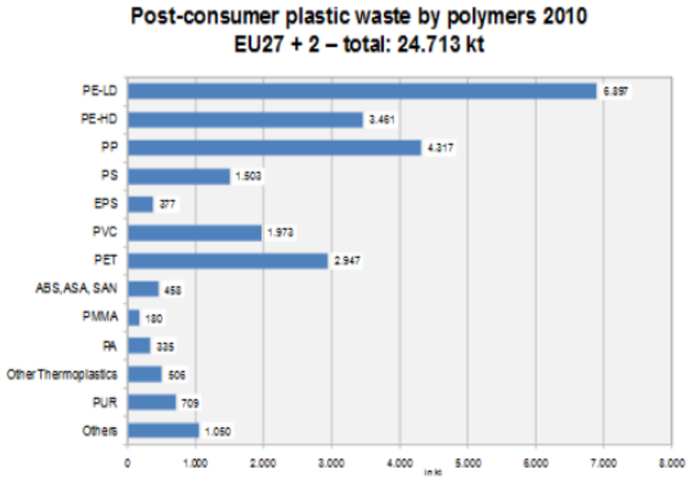
Table 1: Plastic waste types, properties and uses (Source: ACC, 2011)

Polymer name and image	Properties	Uses
Polyethylene terephthalate (PETE, PET)	• Clear and optically smooth surfaces for oriented films and bottles • Excellent barrier to oxygen, water, and carbon dioxide • High impact capability and shatter resistance • Excellent resistance to most solvents • Capability for hot-filling	PET is clear, tough, and has good gas and moisture barrier properties. This resin is commonly used in beverage bottles and many injection-moulded consumer product containers. Cleaned, recycled PET flakes and pellets are in great demand for spinning fibre for carpet yarns, producing fiberfill and geo-textiles. Nickname: Polyester.
High-density polyethylene (HDPE)	• Excellent resistance to most solvents • Higher tensile strength compared to other forms of polyethylene • Relatively stiff material with useful temperature capabilities	HDPE is used to make many types of bottles. Unpigmented bottles are translucent, have good barrier properties and stiffness, and are well suited to packaging products with a short shelf life such as milk. Because HDPE has good chemical resistance, it is used for packaging many household and industrial chemicals such as detergents and bleach. Pigmented HDPE bottles have better stress crack resistance than unpigmented HDPE
Polyvinyl chloride (PVC or V)	• High impact strength, brilliant clarity, excellent processing performance • Resistance to grease, oil and chemicals	Pipe, fencing, shower curtains, lawn chairs, non-food bottles and children's toys. In addition to its stable physical properties, PVC has good chemical resistance, weatherability, flow characteristics and stable electrical properties. The diverse slate of vinyl products can be broadly divided into rigid and flexible materials.
Low density polyethylene (LDPE) Includes Linear Low Density Polyethylene (LLDPE).	• Excellent resistance to acids, bases and vegetable oils • Toughness, flexibility and relative transparency (good combination of properties for packaging applications requiring heat-sealing)	LDPE is used predominately in film applications due to its toughness, flexibility and relative transparency, making it popular for use in applications where heat sealing is necessary. LDPE also is used to manufacture some flexible lids and bottles as well as in wire and cable applications. Plastic bags, 6 pack rings, various containers, dispensing bottles, wash bottles, tubing, and various moulded laboratory equipment
Polypropylene (PP)	• Excellent optical clarity in biaxially oriented films and stretch blow moulded containers • Low moisture vapour transmission • Inertness towards acids, alkalis and most solvents	PP has good chemical resistance, is strong, and has a high melting point making it good for hot-fill liquids. This resin is found in flexible and rigid packaging, fibers, and large molded parts for automotive and consumer products. Auto parts, industrial fibres, food containers, and dishware

Polymer name and image	Properties	Uses
6 PS Polystyrene (PS)	•Excellent moisture barrier for short shelf life products • Excellent optical clarity in general purpose form • Significant stiffness in both foamed and rigid forms. • Low density and high stiffness in foamed applications • Low thermal conductivity and excellent insulation properties in foamed form	PS is a versatile plastic that can be rigid or foamed. General purpose polystyrene is clear, hard and brittle. It has a relatively low melting point. Typical applications include protective packaging, foodservice packaging, bottles, and food containers. PS is often combined with rubber to make high impact polystyrene (HIPS) which is used for packaging and durable applications requiring toughness, but not clarity. Desk accessories, cafeteria trays, plastic utensils, toys, video cassettes and cases, clamshell containers, packaging peanuts, and insulation board and other expanded polystyrene products (e.g., Styrofoam)
7 OTHER Other plastics, including acrylic, fiberglass, nylon, polycarbonate, and polylactic acid, and multilayer combinations of different plastics	• Dependent on resin or combination of resins	Use of this code indicates that a package is made with a resin other than the six listed above, or is made of more than one resin and used in a multi-layer combination.

Table 2: The new RIC symbol (Source: ASTM, 2014)

Resin	Resin Indentification Code-Option A	Resin Indentification Code-Option B
Poly(ethylene terephthalate)	1 PETE	01 PET
High density polyethylene	2 HDPE	02 PE-HE
Poly(vinyl chloride)	3 V	03 PVC
Low density polyethylene	4 LDPE	04 PE-LD
Polypropylene	5 PP	05 PP
Polystyrene	6 PS	06 PS
Other resins	7 OTHER	07 O



Post-consumer plastic waste by polymers - EU 27 + 2 2010	
	in%
PE-LD	27,9%
PE-HD	14,0%
PP	17,5%
PS	6,1%
EPS	1,5%
PVC	8,0%
PET	11,9%
ABS, ASA, SAN	1,9%
PMMA	0,7%
PA	1,4%
Other Thermoplastics	2,0%
PUR	2,9%
Others	4,3%
Total	**100%**

Figure 1: Plastic waste composition (Source: Villanueva & Eder, 2014)

Concurrently, the market shares in terms of generation and use of plastics in the EU in 2010 showed that the five major polymers - that is, PE, PS, PP, PET and PVC - dominated the EU market and accounted for at least 75% of the production demand. Per European Commission report (2014) these shares have remained almost unchanged in the last 3-4 years (from the year of observation) with a variation of just ± 2 % in HDPE, PVC, PP, and PET. In 2015, plastics demand in Europe had reached 49 Mt; 70% of which is concentrated in six countries, namely: Germany, Italy, France, Spain, UK and Poland. In 2016, plastics production showed a slight increase, but was still below pre-crisis level. This increasing trend is expected to continue in 2017 and, perhaps, beyond (PlasticsEurope, 2016).

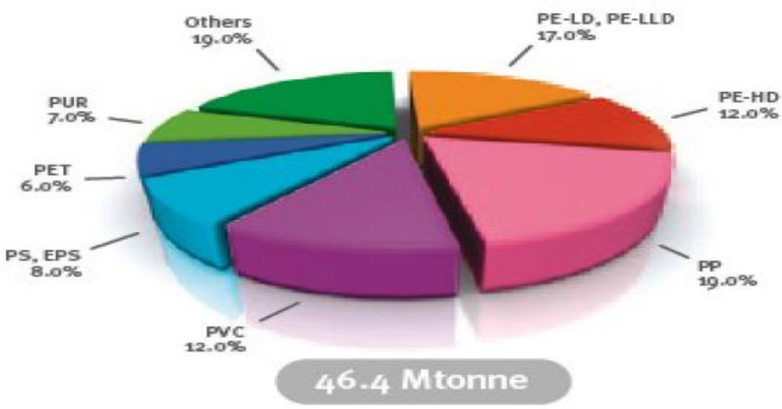


Figure 2: Generation and use shares of plastic polymers in the EU27+NO+CH in 2010

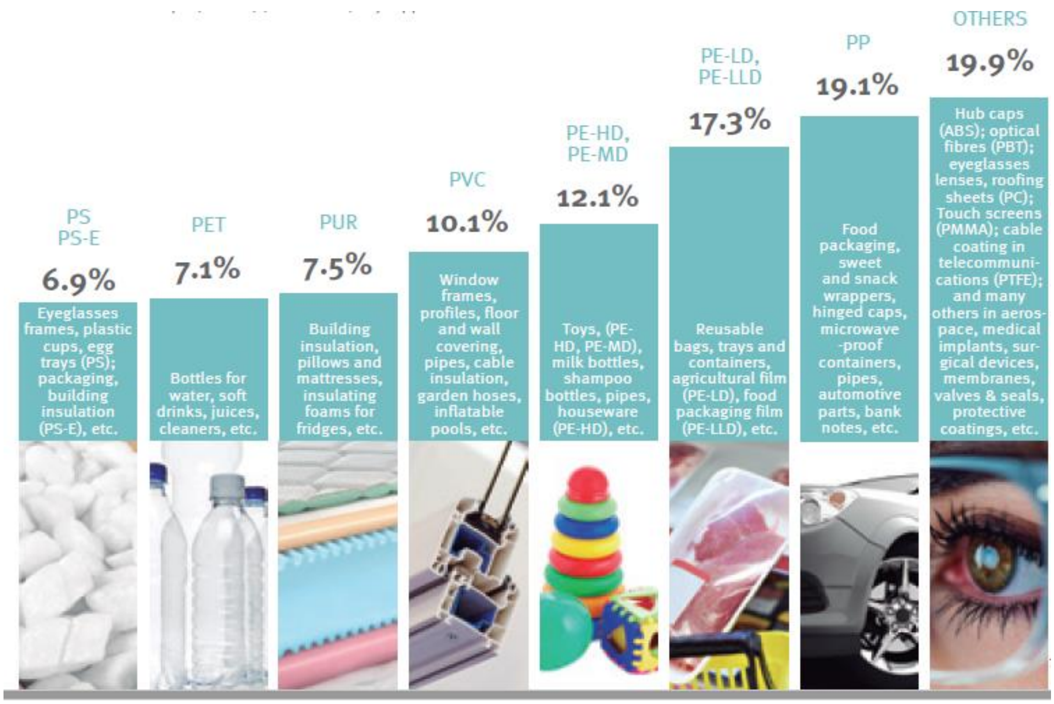


Figure 3: European plastics demand (EU-28+NO/CH) by polymer type 2015

2.2. Plastic Waste Composition Share in MSW, C&D, WEEE, and ELV

The identified sources of waste in general of which plastic wastes form a significant part and usually considered in the analysis and evaluation of waste value chain and other waste matter arising (VTT, 2012) (ZERO waste Scotland, 2012) are:

- Municipal Solid Waste (MSW)/ Household waste
- Construction and Demolition (C&D) waste
- Commercial and Institutional (C&I) waste
- Waste Electrical and Electronics Equipment (WEEE)
- End-of-Life Vehicles (ELV)

Studies as shown that waste composition in general and especially MSW is influenced by factors such as culture, climate, economic development (measure of GDP), geolocation, and energy sources. Waste composition in turn often influences how waste is collected, sorted and disposed.

A country's affluence tends to determine the volume of waste generated (although waste composition is usually provided in weight). High income earning countries have the propensity to increase packaging material wastes generation combined, by proportion, such as paper, glass, metal and plastics than organic waste particularly in MSW composition.

Low-income countries have the highest proportion of organic waste (e.g. Bio-waste or food & yard waste) according to The World Bank (2012) report.

East Asia pacific (EAP), by region, have an estimated 62% of organic waste composition compared to OECD countries with the least at 27%, although the overall amount of organic waste is still highest in the OECD countries combined. In a nutshell, low and middle-income countries have a high percentage of organic matter in the urban waste stream, ranging from 40 to 85% of the total. Paper, plastic, glass, and metal fractions increase in the waste stream of middle- and high-income countries. In some cities, C&D can represent a very significant proportion of the total waste stream generated, and can be as high as 40%. Below is the outlook of the Global Solid Waste Composition and that of U.S, England and Finland.

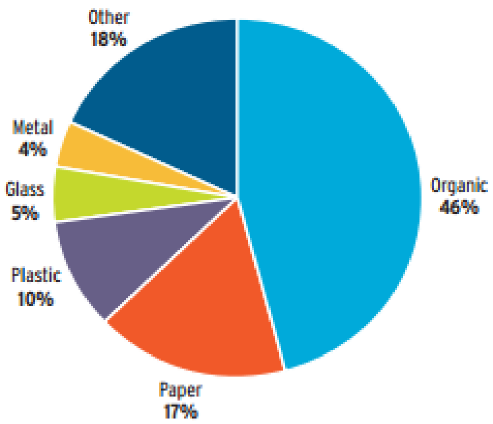


Figure 4: Global Solid Waste Composition (Source: The World Bank, 2012)

With regards to plastics in the mixed waste composition by income, an important observable trend is that of plastic waste dominance among inorganic recyclable fractions as one moves from high-income countries to low-income countries and it relatively constant composition in all the categories.

The versatility of MSW in terms of it definitions (based on region or country), classification and categorization have been extensively studied in journals, publications and other research report. For example, some have argued that all waste, including industrial, commercial, institutional, domestic and street sweeping, collected within the same municipality should be regarded (and defined) as MSW. Some arguments are based on the collecting authority (collector), be it local, private or public authority. In Finland, unlike in most developing countries and some western countries outside the EU, MSW are further categories and

classified as MIXED and SOURCE SEPARATED waste fractions. This is evidence in the Finnish MSW composition has seen in figure 7.

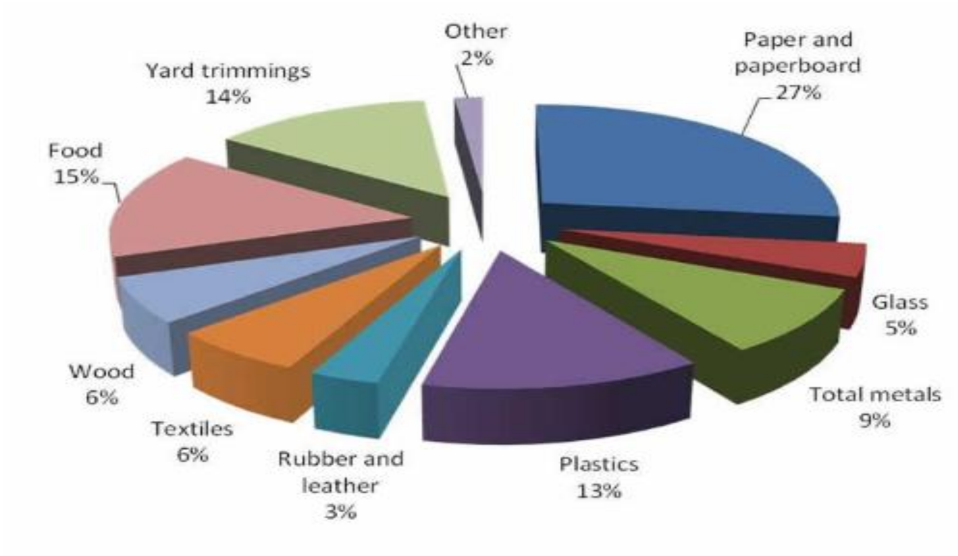


Figure 5: Composition of solid waste generation in the U.S in 2014 (US EPA, 2016)

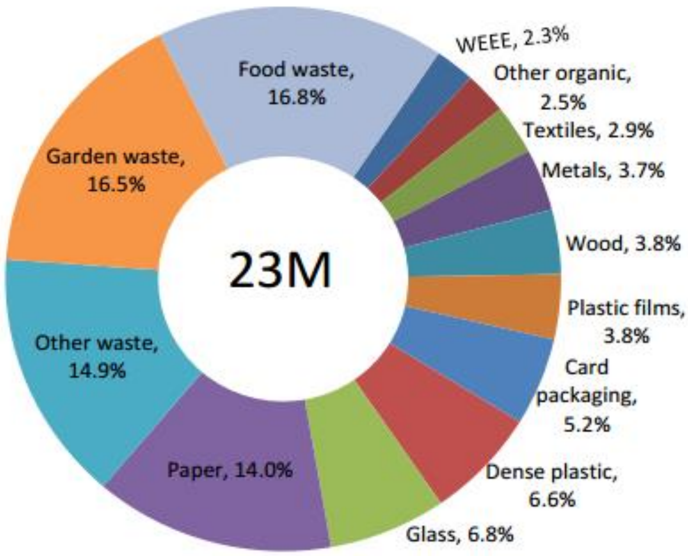


Figure 6: Solid waste composition; England 2010/2011 (Source: DEFRA, 2015)

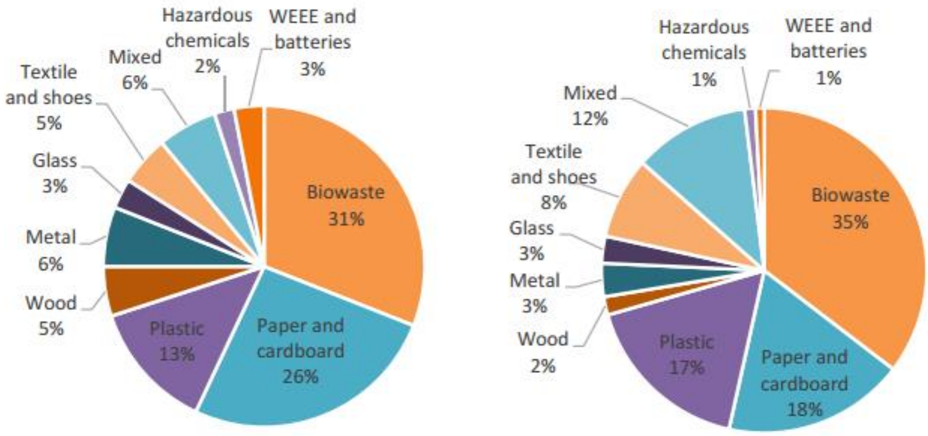


Figure 7: Composition of Finnish MSW (left) and mixed residual solid waste (right) (Source: Havukainen, Heikkinen and Horttanainen, 2016)

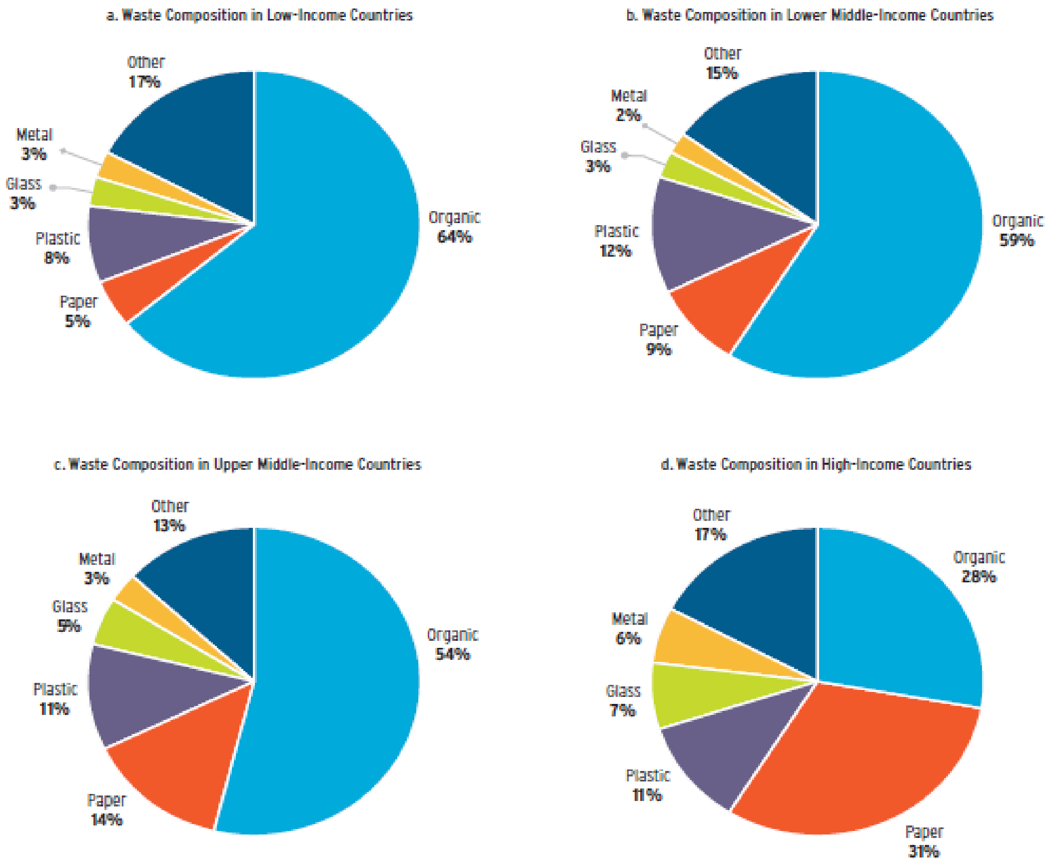


Figure 8: Solid waste composition by income (Source: The World Bank, 2012)

Current available data on plastic waste share by weight in C&D, WEEE and ELV, irrespective of the region or country, have been put at an average of 1.5%, 21%, and 12% respectively. For example, the C&D plastic waste share average composition in Madrid community from 2002 to 2011 is 1.5% (European Commission (DG ENV), 2011); in India, it is 1% and 2% for Massachusetts C&D waste flows in 2007 (DSM Environmental Services, 2008). Information on the Finnish material composition of the C&D waste stream can be found in the *appendix A*.

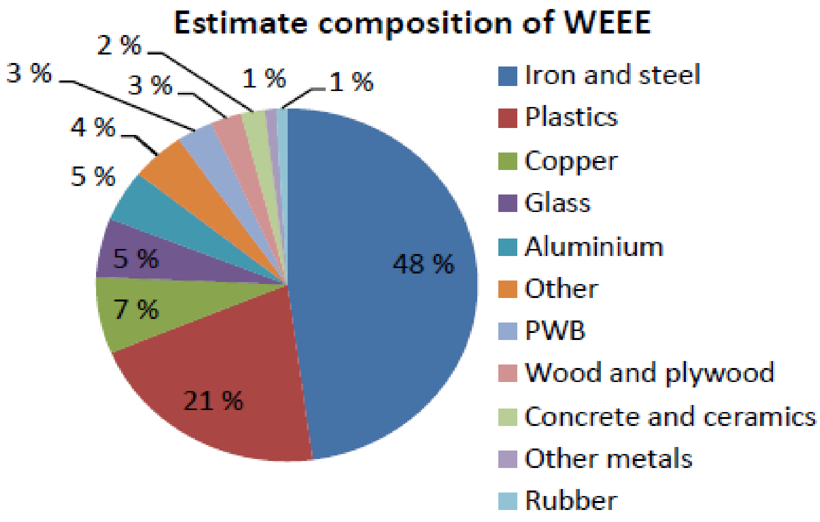


Figure 9: Estimated material content of collected WEEE (Source: United Nations University, 2007)

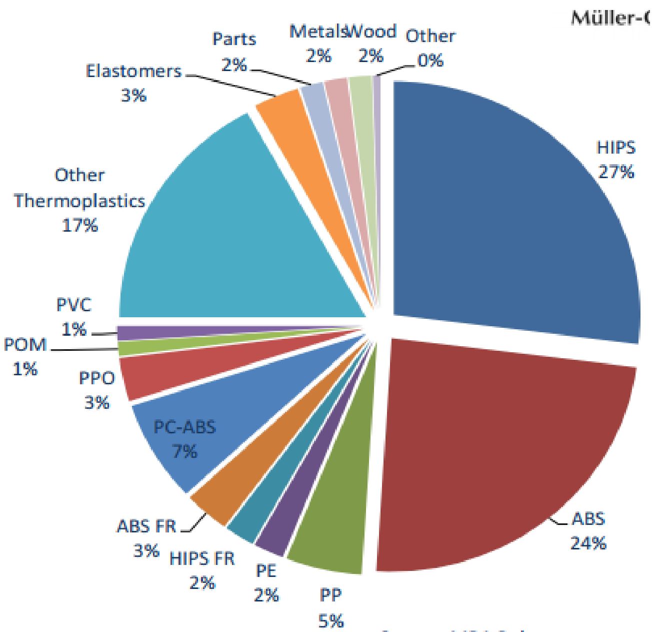


Figure 10: Average composition of WEEE plastics (source: MBA Polymers)

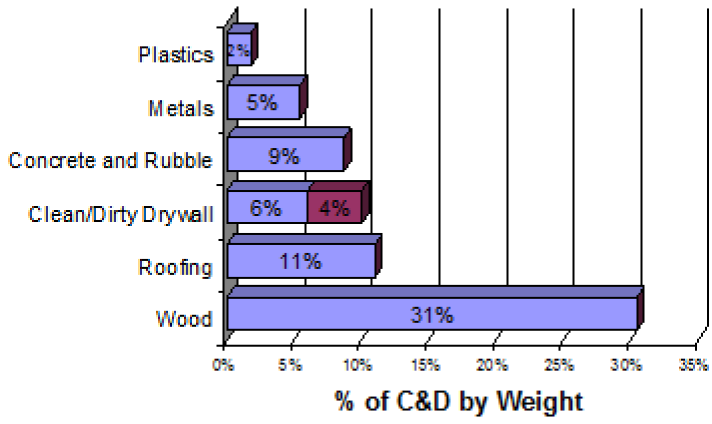


Figure 11: Average composition of C&D waste (Source: DSM Environmental Services, 2008)

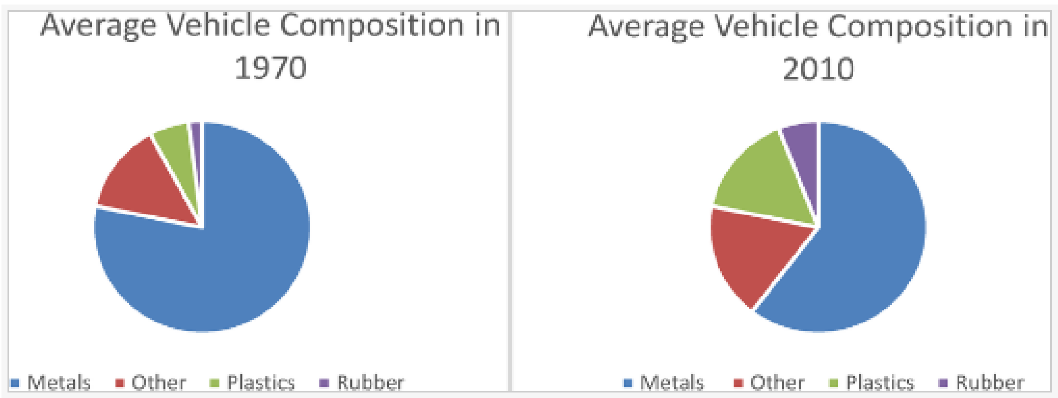


Figure 12: Change in vehicle composition from 1970 to 2010 (Miller et. al., 2014)

2.3. Waste Plastics Collection and Treatment

2.3.1. Source

The main sources of post-consumer or post-use waste plastics are identified as:

- Municipal solid waste (MSW) from household waste and commercial waste
- Construction and demolition waste (C&D)
- End-of-Life vehicles (ELV)
- Waste from electric and electronic equipment (WEEE)

Depending on the origin of the waste plastic, there is almost always need for different degrees of sorting, collection and treatment. The focus of this report is largely on MSW, while C&D was almost not mentioned after this chapter. The reason for this was that C&D poses the least challenge for recycling much like pre-consumer plastic waste needing little

treatment and processing because of the absence of much less contamination compared to MSW. ELV and WEEE stay in between and are mentioned in later analysis.

Most plastic waste from MSW predominantly finds application in packaging and occurs as packaging wastes. They could occupy as high as 80% of the total plastic waste found in households' waste in Nordic countries such as in Norway, Sweden and Finland. Packaging has also earned the highest industry demand by end-use sector of different plastics in the EU27+NO+CH in 2010 (Villanueva & Eder, 2014). This is as shown in figure 13.

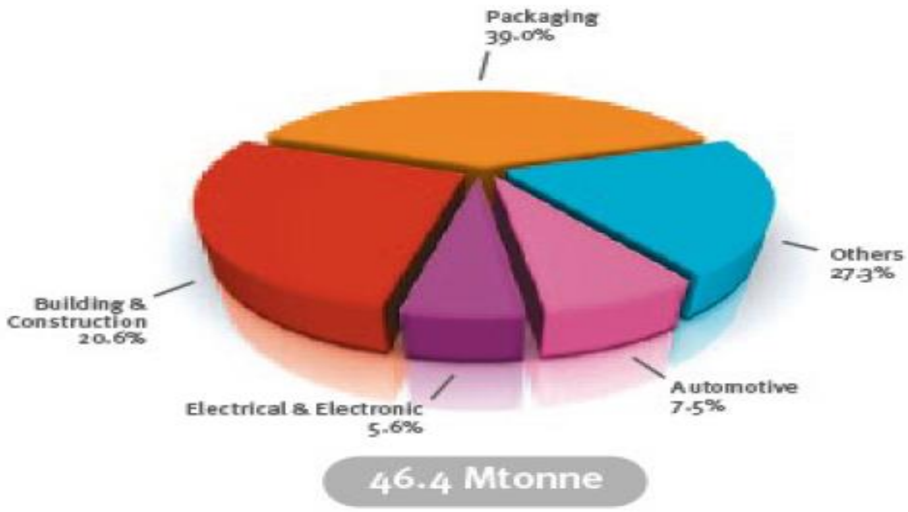


Figure 13: Industry demand by end-use sector of different plastics in the EU27+NO+CH 2010 (source: Villanueva & Eder, 2014)

Clearly, figure 13 depicts packaging (39%) as the main application area for plastics, and then followed by building and construction (20.6%), automotive (7.5%) and electrical and electronic application (5.6%). 73% of this total packaging plastic material is said to be used in households across Europe, while the remaining 27% is mostly used as distribution packaging in industry.

2.3.2. Source Separation and Collection

Source separation: Source separation can be described as a form of multi-stream collection system in which the waste producer is responsible for manually sorting generated material wastes and placing them into designated bins or bags. These waste materials are later collected by collection vehicles with one to multiple compartments. In the collection vehicles, scarcely is a separate compartment reserved solely for plastic waste because of its usual low weight-to-volume ratio which cannot efficiently utilize the capacity of such

compartment. Consequently, plastic waste is often collected together with other dry materials.

Collection: There exist various collection schemes and strategies for the collection of plastic wastes and other waste fractions. Different applicable strategies can become adaptable to different schemes. All the different strategies are typically categorized into single-stream (co-mingled) or multi-stream (separately collected) collection strategies. In other cases, they may be referred to as mono-material and multi-material collection strategies. Some of the known collection strategies are:

- Single stream or comingled collection strategy- referring to the collection of all dry recyclables materials into a single bin or bag.
- Separating all fraction, including biowaste, into their individual bins or bags and the inclusion of bin or bag for residual waste – i.e. multiple streams collection strategy.
- Separating fractions into biowaste (i.e. food waste and garden/yard waste), and other dry waste-[dry mixed waste] (i.e. plastics, metal, wood, paper and cardboard, glass and others) – i.e. single-stream collection strategy.
- Separating fractions into organic waste (including biowaste, paper and cardboard, and wood) and inorganic waste (including plastics, metal, glass and others). Note, plastics is derived from fossil, but it is not biodegradable in short term. This is another single stream collection strategy that is unpopular.
- Dual streams collection strategy involving separating biowaste; paper; and other mixed dry waste, which includes plastic waste, into separate fractions. Another multi-stream collection strategy type.
- Mixed MSW collection strategy i.e. multi-material collection system

Note:

- Other waste referred to here may include other miscellaneous waste such as rubber, textile, WEEE and trace of inert and hazardous fractions.
- Mixed waste including all fractions (i.e. organic and inorganic) could be source generated (in absence of source separation) or remain/residue of source separation of all fraction.

Collection schemes for recyclables, be it for materials (e.g. plastics) or nutrients (e.g. biowaste), are often established with the purpose of recovering valuable resources and

reducing the amount of wastes going to landfills or incinerating plants. The three main collections schemes recognized in EU are:

- Source-separated or multiple-stream collection scheme
- Co-mingled fractions or single-stream collection scheme
- Residual waste or mixed waste collection scheme

These schemes and their adopted strategies utilizes some sorts of collection systems for the recovery of these valuable resources, namely:

- Kerbside collection systems
- Bring systems
- Deposit-and-return systems

Ostensibly, plastic wastes from private households are often collected in kerbside collection systems either as co-mingled or source-separated fractions. In areas where kerbside collection is not feasible or convenient by reason of either very low or very high housing density; bring systems are usually deployed. Deposit-and-return systems are designed for returning beverage containers (i.e. glass bottles, cans-majorly foil aluminium, and plastic bottles-predominantly PET) and have a very high rates of bottles and cans being returned.

Households plastics waste from private homes not found in any of the co-mingled or source-separated fractions are eventually a part of the residual waste. In other words, plastics not source sorted ends in the residual waste fraction, which until now in Europe and other countries of the world are being incinerated or landfilled. The presence of plastic waste in residual waste seems unavoidable as source-separation can never be 100% efficient. However, recovering and recycling plastics from residual waste can be a promising way of increasing plastics recycling rate especially since there is an established collection scheme for it already across Europe and many other countries of world (Plastic ZERO, 2013).

Evidentially, plastic packaging and packaging as an application area have been the main focus and target of almost all the collection schemes and systems. This may be largely due to producer responsibility on packaging introduced in several European countries; putting the burden of collecting and recycling of packaging waste fully or partly on manufacturers and or fillers. Another reason may be the fact that packaging has the highest industrial demand by end-use sector. And lastly, it may be that the large and well defined fraction of household plastic wastes are predominantly plastic packaging.

This notwithstanding, other application areas and product groups such as cars and automobile; electrical and electronic equipment; and construction and building parts have their own established collection systems as well. However, challenges still remain with variety of other products such as furniture, houseware, toys, tools, instruments, and textiles. Efficiently recovering plastics from these products represent or constitute a future challenge to the waste management system as to how plastics from these products can be collected, processed and recycled.

Efficiency of Collection Systems: Collection scheme efficiency is mostly defined as the capture rate or percentage of potential amount of target material captured or collected by the collection scheme. The quantity of total material captured or collected in Kg/household/year can always be determine whereas potential amount may not always be known, and therefore, it may not be possible always to calculate the capture rate. However, separate studies by Larsen (2009) and Petcore (2014) revealed some rough estimates for plastic collection capture rates under the different types of collection systems (table 3).

Table 3: Plastic collection capture rates

Type of collection system	Share of waste captured
Kerbside collection systems	40-60% of targeted recyclables, low degree of material contamination (Petcore, 2014) 30-76% of plastic packaging (Larsen, 2009)
Bring systems	10-15% of targeted recyclables, quite high contamination level: 10-30% (Petcore, 2014) 17-57% of plastic packaging (Larsen, 2009)
Deposit-and-return systems	90% of bottles in PET deposit programmes, very low levels of contamination (Petcore, 2014)

These values are most likely hinged on the motivation of the persons involved or participating in waste collection and segregation exercise. Motivation for certain behaviour in turn is a reflection of psychological and situational factors, as well as environmental values. However, variations in the performance of collection schemes has been majorly ascribed to demographic factors such as level of deprivation or affluence, age and number

of persons in the household among other minor factors. These other factors could be the number and or range of targeted materials, use of bins or bags, collection strategies and time of collection (Plastic ZERO, 2013).

2.3.3. Sorting and Separation

Sorting refers to here, is the centralized separation of material fractions at processing and treatment facilities or plants utilizing different kinds of separation technologies for material separation and decontamination of polymers as well as production of feedstock for the conversion process. Plastic waste not sorted at the source (source separation/sorting) and or treatment plant (centralized sorting/separation) would eventually undergo thermal treatment or be landfilled. More about sorting and separation technologies can be found in chapter 4 of this report.

Looking at it from the perspective of waste management system; collection and sorting are a vital part of material value chain for recycling of plastic waste. Basically the aim is to separate plastics from other materials and produce feedstock through mainly mechanical recycling for manufacturing of new plastics or for energy purpose.

Figure 14: Plastic waste management system value chain (source: Plastic ZERO, 2013)

Sorting plastic waste is a composite process of separating plastics from non-plastics content and separating plastic waste itself into the different plastic polymers and or colours. The objective is to recycle plastic materials into useable polymers with a pure stream of one or two polymers. Inefficient sorting may lead to mixed plastic material that may not be usable for recycling, or for which recycling may not be economically feasible. In other cases the mix of plastic polymers may even constitute safety or health risk for example mix of PVC and PET.

2.3.4. Recycling

According to WFD EC/98/2008, recycling was described as a recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original purpose or other purposes. Whilst it involves the reprocessing of materials, it does

not include reprocessing to materials that are to be used as fuels or for backfilling operations. Neither does it includes reprocessing materials for energy recovery.

The two main recycling types are mechanical and chemical (or feedstock) recycling. Mechanical recycling may involve the melting of polymers, but not its chemical transformation. Mechanical recycling is prevalently used in the EU while chemical recycling is widespread in other regions of the world. For example, in Japan, around 5% share of waste plastics was reported to have been treated using chemical recycling (Villanueva & Eder, 2014). To a much smaller degree, chemical recycling also takes place in the EU, where a certain degree of polymeric breakdown occurs.

Mechanical recycling is the focused choice of this report. Approximately 87% of mechanically recycled plastics are converted to recycle raw plastic intermediates (e.g. flakes, regrind, agglomerates, pellets, profiles and granulates) while the remaining 13% are converted directly into products. Plastics that are directly reprocessed into products often come from more contaminated streams and consequently results in end uses with lower quality demands such as flower or plant pots, outdoor furniture, door or car mats. The higher quality plastics can be used for a wider range of applications, with intermediary shapes as pellets and granules. The basic operations that may be involved in mechanical recycling are presented in table 4.

Generally, most mechanically recycled plastics are from commercial and industrial sectors, while bottles are recovered mainly from household sources. Improvements in the sorting and separation processes could help develop the use of mechanical recycling as a means of plastic waste treatment method for households. Terminologies used in describing plastic recycling can be seen in table 5.

Table 4: Mechanical recycling operations (source: Villanueva & Eder, 2014)

Process	Description
Cutting	Large plastic parts are cut by saw or shears for further processing
Shredding	Plastics are chopped into small flakes, allowing the separation of materials (e.g. metals, glass, paper) and plastic types (e.g. PET bottles from PP lids).
Sorting	Additional sorting (e.g. NIR) once the material has been shredded.
Contaminants separation	Contaminants (e.g. paper, ferrous metals) are separated from plastic in cyclone separators and magnets. Liquids/glues can be separated in a wet phase (see below).
Floating/Cleaning	Different types of plastics are separated in a floating tank according to their density. The density of the liquid can be modified to enable separation (e.g. adding salt to water). The wet phase can also be used for washing residuals (e.g. organic)
Extrusion	The flakes /pellets/agglomerates are fed into an extruder where they are heated to melting state and forced through, converting into a continuous polymer product (strand).
Filtering	The last step of extrusion may be filtering with a metal mesh (e.g. 100-300 micron)
Pelletizing	The strands are cooled by water and cut into pellets, which may be used for new polymer products manufacturing.

Table 5: Plastic recycling 'cascade' terminology (adapted from Hopewell et.al, 2009)

ASTM D7209-06 standard definitions	Equivalent ISO 15270 standard definitions	Other equivalent terms
Primary recycling	Mechanical recycling	Closed-loop recycling
Secondary recycling	Mechanical recycling	Downgrading, downcycling
Tertiary recycling	Chemical recycling	Feedstock recycling
Quaternary recycling	Energy recovery	Valorisation

2.4. Plastic Waste Treatment: A Life Cycle Thinking Perspective

While we are seeking possible increase in recycling rate of plastic waste and thinking of plastic recyclates as valuable product; it is equally important to begin to consider the environmental impacts of each phases of the recycling process involved. Interestingly,

recycling is one of the waste management options to be quantitatively evaluated for environmental impacts of a product over its generation to it recycling phase.

This view underscores the importance of Life Cycle Thinking (LCT) in waste management. In this report, LCT considers the potential environmental impacts of plastic waste from source through to the final recycling stage. Successfully reducing the amount of virgin plastic materials that will ultimately be turned into waste plastics will avoid GHSs emissions from extraction, processing, transportation, and end-of-life of plastics; and the resources (i.e. mainly energy and water resources) that would be required to produce those (Depoues & Bordier, 2015).

Figure 14 of section 2.3.3 of this chapter depicts the layout of the different phases involved in the recycling of waste plastics. The significance of this is to weigh the environmental impact balance of plastic waste in it unrecycled state (to be landfilled or/and unleashed into the environment) and when recycled as well as its comparison with other waste management options such as incineration-with or without energy recovery- and production of SRF.

EU sustainability strategy and waste management directive have provisions for alternatives in cases where plastic waste generation is not preventable; reusable, not feasible; and recycling not sustainable, in terms of environmental impact and resources consumption, and in some cases, not economically viable. For example, when and if plastics cannot be sustainably recycled such non-recyclable plastics can provide a valuable energy resource in advance thermal energy recovery systems thus contributing significantly to energy security and the displacement of virgin plastics from fossils fuels.

Another dimension to the relevance of LCT in plastic recycling is to be able to develop and adopt the least impact environmental technologies for the recycling of plastics waste. Well documented LCA of any recycling process especially that of plastic waste recycling, much like any product manufacturing process, is most likely to support the policy and decision making of businesses and governments.

Recycling has always been thought to be a means to reduce emission and the consumption of virgin materials, and the conservation of other natural resources such water, air, land and energy, but this may not always be so. According to some studies, concerns still remain on the generation and treatment of waste plastics depending on whether the waste plastics are a

part of residual waste, municipal solid waste, co-mingled fraction or separately collected fraction.

From the view point of waste management hierarchy and results from various life cycle assessments (LCA), recycling has been concluded to be an environmentally better treatment method than incineration and landfilling. This overarching conclusion too may not hold for all types and qualities of plastics; for example, if recycling leads to downcycling or level/rate of replacement of virgin plastics is considered poor or there is much higher food contamination (WRAP, 2008; Plastic ZERO, 2013).

Whilst the environmental impact of collection and sorting technologies may be more related to the use of energy for running the processes and the emissions released during those processes as well as water for cleaning of the plastics; the environmental performances of sortation technologies should be a determining factor in the choice of separation technologies. However, comparing the different separation technologies and collection systems involved in recycling without due consideration for the quality and use of the produced polymer recyclates in a holistic manner, may not always lead to the right conclusion of which one is the better.

2.5. Statistics on Plastic Waste Recycling Rate of Different Countries

Data available on global plastic packaging and PET bottles recycling rate as of 2013 reveals an average recycling rate of 14% for all plastics categories and 55% for PET bottles. Recycling rate of plastic bottles in the U.S in 2014, according to material type including PET, HDPE (natural/clear), HDPE (pigmented/coloured), PVC, LDPE, and PP, is estimated at an average of 31.8%. This represents a slight increase from 31.2% in 2013 (Statista, 2016). In 2008, according to EPA reports, the recycling rate of various plastics items including packaging and bottles was put at 6.8% of total plastic waste generated. Of this percentage, only 13.3% of plastic packaging was recycled (LeBlanc, 2016).

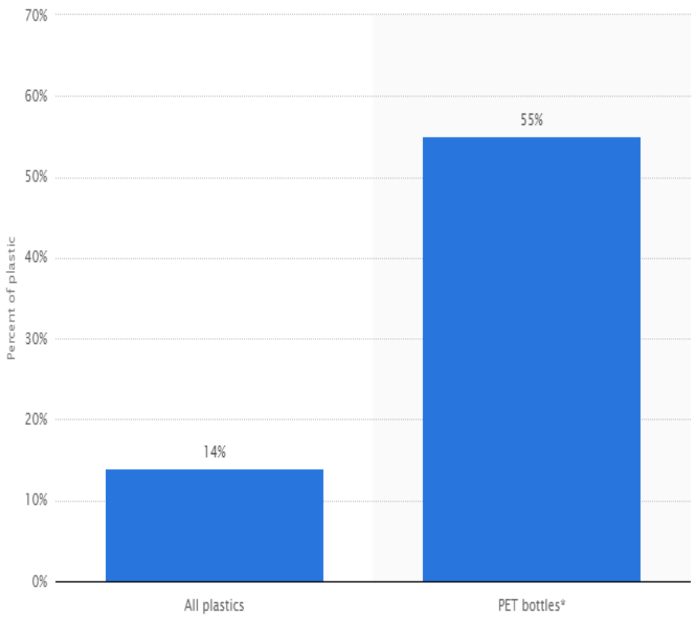


Figure 15: 2013 recycling rate of all plastics and PET bottles worldwide (Source: Statista)

In Singapore, overall recycling rate was estimated at an average of 61% in 2015, only 7% of all plastic waste generated was recycled (NEA, 2016). This represents a decline from 11% in 2013. In Spain, according to the recent Spanish association Cicloplast report, 2.151 Mt of plastic wastes are generated annually: 34% are recycled, 17% valorised for energy purpose and 49% landfilled. This had made Spain one of the leading European nations in plastics material recycling, only surpassed by Norway, Sweden, Germany and Ireland (AIMPLAS, 2016).

Many EU member countries including Switzerland and Norway have developed more successfully recycling programs enabling them to be at the top of the recycling game. One such program is the ban on landfill; and the set recycling targets.

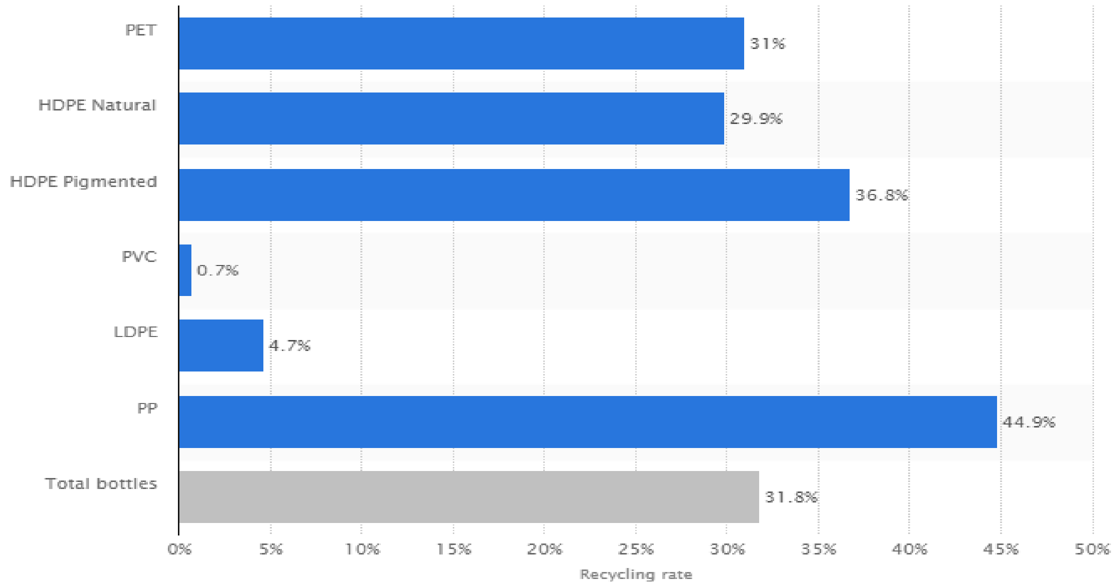


Figure 16: 2014, recycling rate of plastic bottles in the U.S, by material type (Source: Statista)

The annual average post-consumer plastics waste generation in EU 28+2 (i.e. including Norway and Switzerland) from 2006 to 2014 is estimated at 25.8 million tonnes. This is a representation of the official waste streams (i.e. upstream) for total post-consumer plastics waste. Of this tonnage, at least 7.5 million tonnes was collected for recycling. In this same year, plastic packaging, amongst the different plastics applications, reached the highest recycling rate with 39.5% (based on in-put quantities into recycling facilities). This represented more than 80% of the total recycled quantities. The overall EU 28+2 post-consumer plastics waste recycling rate, in 2014, is put at 29.7%. Whereas 39.5% was recovered for energy use and 30.8% disposed in landfill (PlasticsEurope, 2016). Figure 17, 18 and 19 below depict individual EU member countries' (including Norway and Switzerland) recycling rate as of 2012 and 2014.

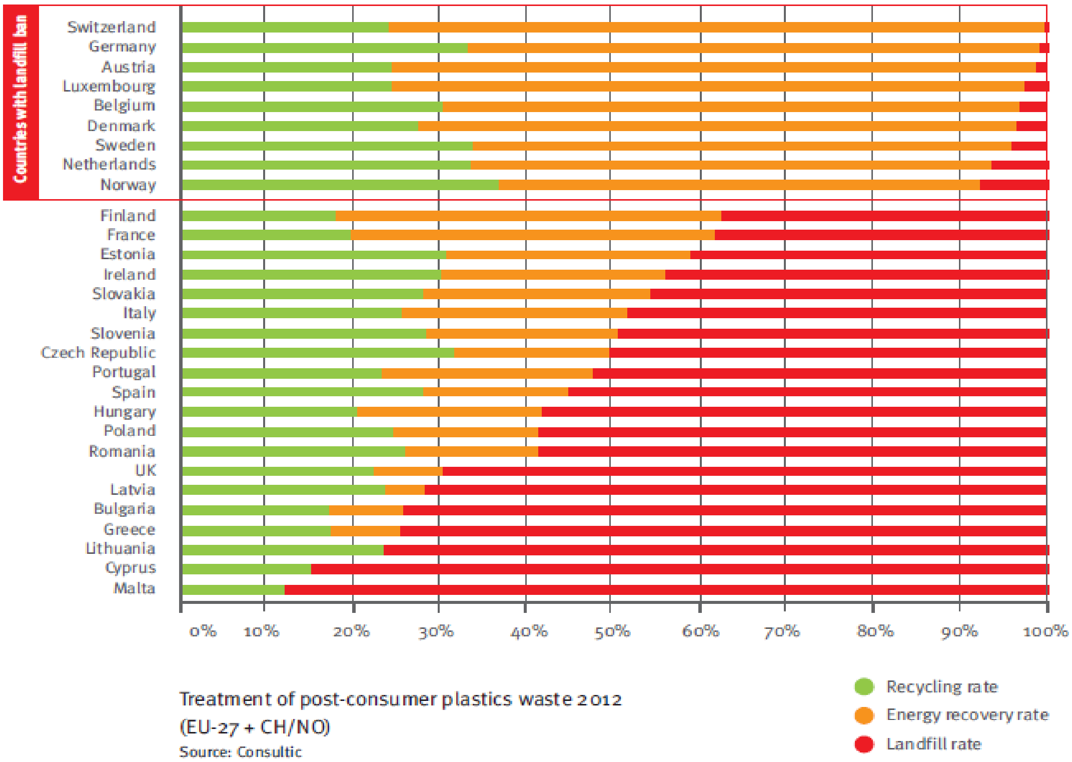


Figure 17: 2012, post-consumer plastic waste treatment (Source: PlasticsEurope, 2015)

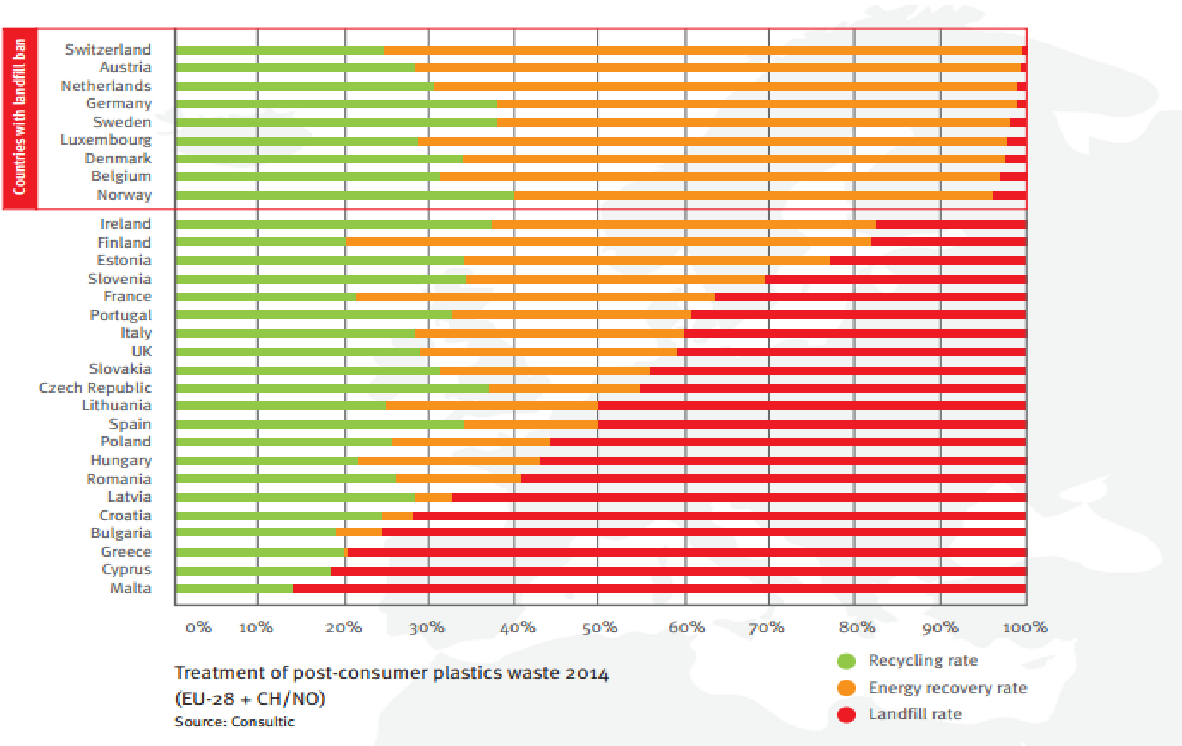


Figure 18: 2014, post-consumer plastic waste treatment (Source: PlasticsEurope, 2015a)

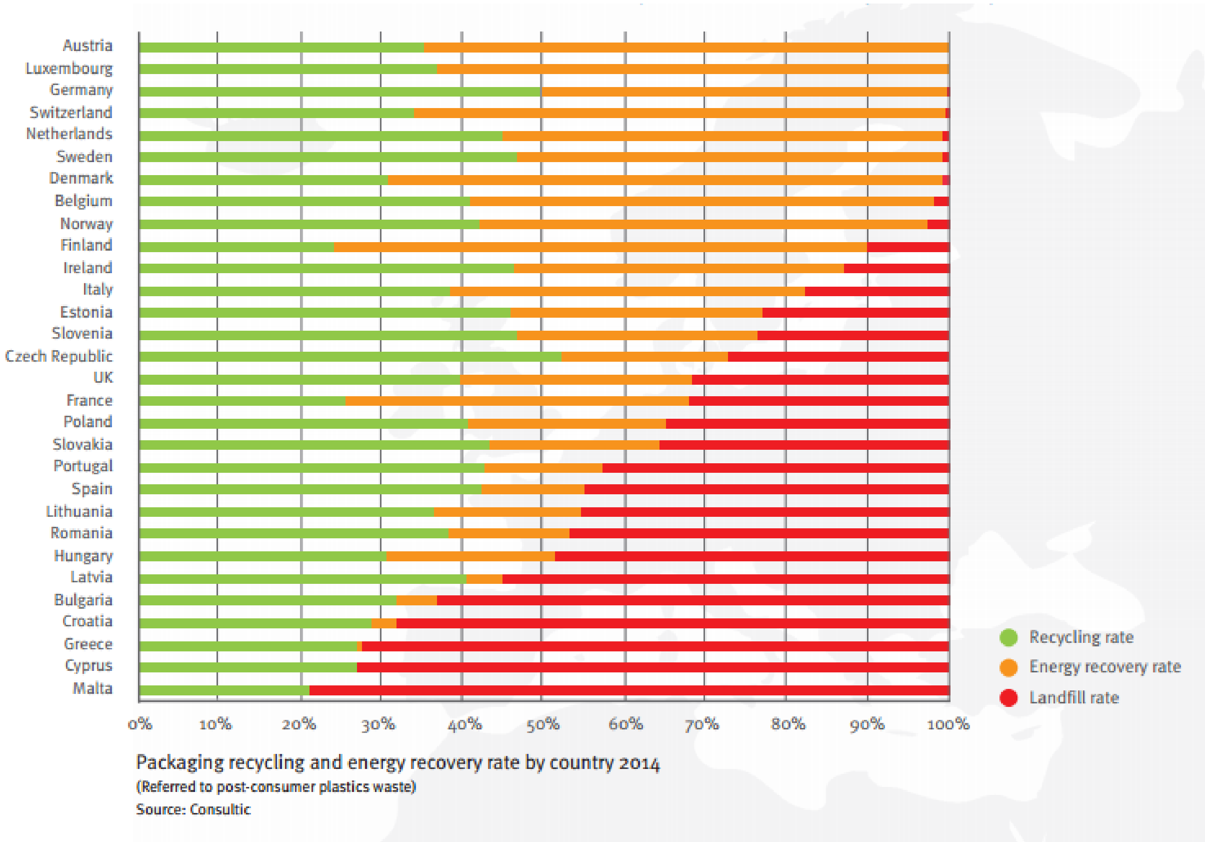


Figure 19: 2014 plastic packaging representation with the highest recycling and energy recovery rates amongst total waste plastics in the EU (Source: PlasticsEurope, 2015a)

2.6. Challenges and Opportunities for Improving Plastic Waste Recycling

There exist several challenges right from the generation of post-consumer plastic wastes to the point where they are made ready as a product or raw material for the production of other products. Right from the source, it is very much unlikely that plastic waste could be separated correctly into it various polymer types. This is especially so with PET, PE and PP which are the major components of polymers found in household MSW, as well as separating PET bottles from their PVC top covers.

Economically, it is not feasible and viable to have or create different separate bin or bag for all type of available polymers present in post-consumer waste. Conventionally, all known polymer present in post-consumer waste are either collected together as plastic waste with a separate bin or bag, or along with other dry recyclables. However, advances in technologies and systems for the collection, sorting and reprocessing of recyclable plastics are creating new opportunities for recycling.

2.6.1. General Collection and Sorting Challenges and Opportunities

In case you are wondering like me why rigid plastic packaging has always been the focus of material recovery collection and sorting. The answer is not far fetch. Flexible plastic packaging tends to be problematic and difficult to handle at material recovery facilities. For example, the low weight-to-volume ratio of plastic bags and films and ability to mask other items or get entangled, make it less economically attractive to investment and technically difficult to assess.

Increasing the recycling of films and flexible packaging may include separate collection, and or investment in extra sorting and processing facilities at recovery facilities for handling mixed plastic wastes. High performance sorting of the input materials is necessary and required for high levels of yield and purity for successful recycling of mixed plastic wastes (Hopewell et. al. 2009). Additionally, there may be further need to develop the end-markets for each polymer recyclate stream.

Studies suggest that if rigid packaging for example bottles, jar, tray and other containers are devoid of PVC or PS, which are problematic to sorting, then all rigid plastic packaging could be collected and sorted with minimal cross-contamination. One such opportunity is to select labels and adhesives to maximize recycling performance. Similarly, designing for the environment, for example, through the use of TRACER technology, has the ability to track and eliminate restricted substances from plastics. It has been claimed that this will dramatically and effectively increase recycling of packaging and non-packaging plastic wastes (WRAP, 2010).

2.6.2. Separation Challenges and Opportunities Specific to Plastic Recovery Facilities

Although the goal of every closed-loop plastic recycling and or recovery facility is to further maximize and or potentially improve both the quantity and quality of recycled resins as well as provide eco-efficiency by decreasing waste fractions, virgin resources, energy and water use. To achieve these, recyclers may have to contend with a number of bottlenecks peculiar to plastic waste. Below is an outline of possible challenges recyclers must overcome at plastic recovery facilities depending on the stream composition.

- Separation of films from rigid plastics, and thereafter the sorting of the films
- Detection of PET bottles covered with PVC sleeve labels
- Elimination of PVC bottles from PET stream
- Colour separation of PET for bottle to bottle applications

- Separation of multilayer bottles (e.g. PE/PA/EVOH)
- Separation of PET grade (PET-G) from bottles and trays
- Separation of black or dark plastics which cannot be sorted by NIR
- Separation of unwanted or restricted substances such as BFR and POP-PBDE
- Separation of PP filled Talc
- Separation of PAs
- More recently, separation of important polymer composite materials

In tackling these challenges, combined sorting, predominantly of automated separation technologies have proven to be handy and successful in most cases (not in all cases). Existing automated sorting machines based on optics (i.e. sensor) and density separation are being largely used by recyclers, material recovery centres and other users for this purpose. Apart from providing sorted fractions with high quality and purity levels, these technologies, are also crucial to removing materials containing unwanted substances, thus, reducing uncertainties in the composition of the target material. However, these and other existing technologies such as electrostatic based technologies have failed to completely address recycling problematics.

Consequentially, attempts at numerous research works are currently ongoing to develop technologies able to tackle BFR related issues, remove all particles containing POP-PBDEs and sort black plastics with equally high and even higher yield and purity near complete close-loop levels compared to the existing technologies. Unfortunately, at the moment, most of these emerging separation technologies being developed are still failing to provide industrially relevant and matured technologies (Frerejean, 2014). Specifics about the emerging and existing technologies can be found in chapter 5 of this report.

3. MIXED WASTE PROCESSING FACILITIES

Mixed waste stream processing is a mechanical and or biological process that separate recyclable materials and or nutrients derived from residual MSW and or unsorted mixed household waste. This separation process is normally carried out at mixed waste processing facilities (MWPFs) -also referred to as residual waste treatment facilities (RWTFs) and or MBT facilities- where a variety of new and existing technologies are used to sort recyclables from a stream of mixed waste. MWPF can be configured as a stand-alone facility processing the entire mixed waste stream or combined with material recovery facility (MRF) and source-separated collection of recyclable fractions.

Earliest designs of MWPFs were strictly tailored for combustion-based energy recovery, Today, MWPF is attracting renewed interest across the globe as a way to address low participation rates and other associated problems with source-separated collection recycling system to prepare feedstock for conversion/reclamation and/or fuel products (i.e. RDF/SRF) (ACC, 2015).

Advances in sortation/separation technologies make today's MWPFs different, versatile and in every sense, better than older versions. This has enabled significantly higher diversion rates from landfill and more recoverable streams. For example, the use of optical near infrared (NIR) light and sensors have dramatically increased the overall recovery of plastics for recycling and/or energy recovery in operational facilities across European, America and Asia (Lee et. al, 2016; WRAP, 2010). Purpose behind most residual waste treatment processes could be any or combination of the following:

- Reduce the volume of waste material for final disposal
- Stabilized the final waste residue to be disposed
- Recover material for energy
- Recover material for recycling (the main concern of this report)
- Recover material for other applications

Residual waste management systems are complex because of the wide variety of waste fractions involved, consequently many different treatment methods are existing and many new ones are emerging and being developed. Three main types of residual waste treatment plants or facilities are:

- Mechanical Biological Treatment (MBT) plant
    - Waste to Resource (WTR)
- Residual Waste Treatment Facility (RWTF)
    - Waste to Energy (WTE)
- Landfilling Facility
    - Bioreactor
    - Encapsulation

3.1. Mechanical Biological Treatment

MBT appears to be a natural choice for the handling, treating and processing of residual MSW (i.e. waste not collected separately for recycling) and mixed household waste (i.e. unsorted bulk of MSW) as well as commercial and industrial wastes. Being a type of waste processing facility, MBT combines a number of different technologies for the sorting of dry recyclables, majorly plastics and metals, and with a form of biological treatment for the organic-rich fraction as composting or anaerobic digestion (AD) (CIWEM, 2013). MBT is a generic term use for integration of several mechanical processes commonly found in other waste management facilities such as MRFs, composting or AD plants. It basic principle of operation is either to separate waste and then treat: or to treat waste and then separate (DEFRA, 2013).

Historically, the concept of MBT originated from Germany where it is now an established waste treatment method and standardized waste separation technique. The major drivers for the development of these technologies have been ascribed to regulatory restrictions on landfill space, and then subsequent landfill bans, and the search for alternatives to incineration as well as increased costs of alternative disposal (DEFRA, 2013). And now, MBT is already helping to deliver sustainable waste management across Europe, especially in major European market such as in Germany, Austria, Italy, Switzerland, Netherlands, and fast growing in the UK. Asian countries such as Japan, Singapore, and Korea have proper and planned solid waste management systems utilizing MBT technologies (Lee et. al., 2016). Countries with much less sophisticated waste collection system stand to benefit the most from MBT for many reasons, which are largely economic related.

Recycling performance of MBT plant system are able to recover a further 15-20% from residual waste when plastics, metals, as well as inert materials (including glass) are removed (CIWEM, 2013). In MBT systems, materials are extracted according to their value and mass

diversion from landfill, with metals and rigid plastics being the main target materials. There is however trend towards glass and aggregate recovery for use in construction and as Alternative Daily Cover (ADC) at landfill sites. This inherently low grade material would be subject to achieving suitable material quality, though this would not count towards recycling performance or diversion from landfill (DEFRA, 2013). The main target materials may include biowaste or organic-rich material fraction when mixed household MSW is involved instead of residual waste.

Recyclates derived from residual waste or mixed waste that qualify as recycling using MBT systems could contribute significantly to both national and local targets. Metals are the easiest to separate using these systems and could boost local authority recycling rates by approximately 5% (CIWEM, 2013). Notwithstanding, individual recycling rate is dependent on the waste composition and the MBT technology used. The choice and quality of materials to recover are usually a function of local authority contracts, quality standards and pricing model from reprocessors amongst other factors. In some cases, materials with greatest carbon savings when recycled are preferred. This has tendencies to drive down the overall carbon footprint of the waste management industry.

The drive for quality is key when deciding on the configuration and MBT technologies to be deployed. This is beneficial to the resource recovery market such as the end-market and the reference market or any other market outlet. Consequently, new and advance state-of-the-art MBT technologies are being developed; and in some cases, modification of older MBT plants are being made to extract materials of increasingly higher quality and purity.

DEFRA (2013) in its report stated that the application of such techniques as optical sorting technologies in MBT processes have the potential to recover high value material-specific waste streams, such as segregated plastic by polymer type. It however pointed out that the capital costs associated with installing such technologies are high and that costs-benefits would be hugely influenced by the effectiveness of any recycling achieved upstream through kerbside collection systems designed to limit the quantity of recyclable materials present in residual waste. DEFRA further acknowledged that the application of such techniques in MBT processes in the UK is limited and it effectiveness yet to be fully developed to date (i.e. 2013) in United Kingdom.

Emerging MBT technologies are however concentrating more on material recovery rather than energy recovery from MSW. Consequently, the mechanical phase of the treatment is gaining more attention for the recovery of fractions of high value such as plastics and metals and those of less value such as paper and wood. The biological phase is however being developed to reduce contaminant to the lowest barest minimum with the same being pursue vigorously at the mechanical phase. Additionally, the phases are well accelerated and well controlled in state-of-the-art MBT. This is the current trend in country such as Germany, Austria and Switzerland and emerging in some EU member countries, and some emerging economy.

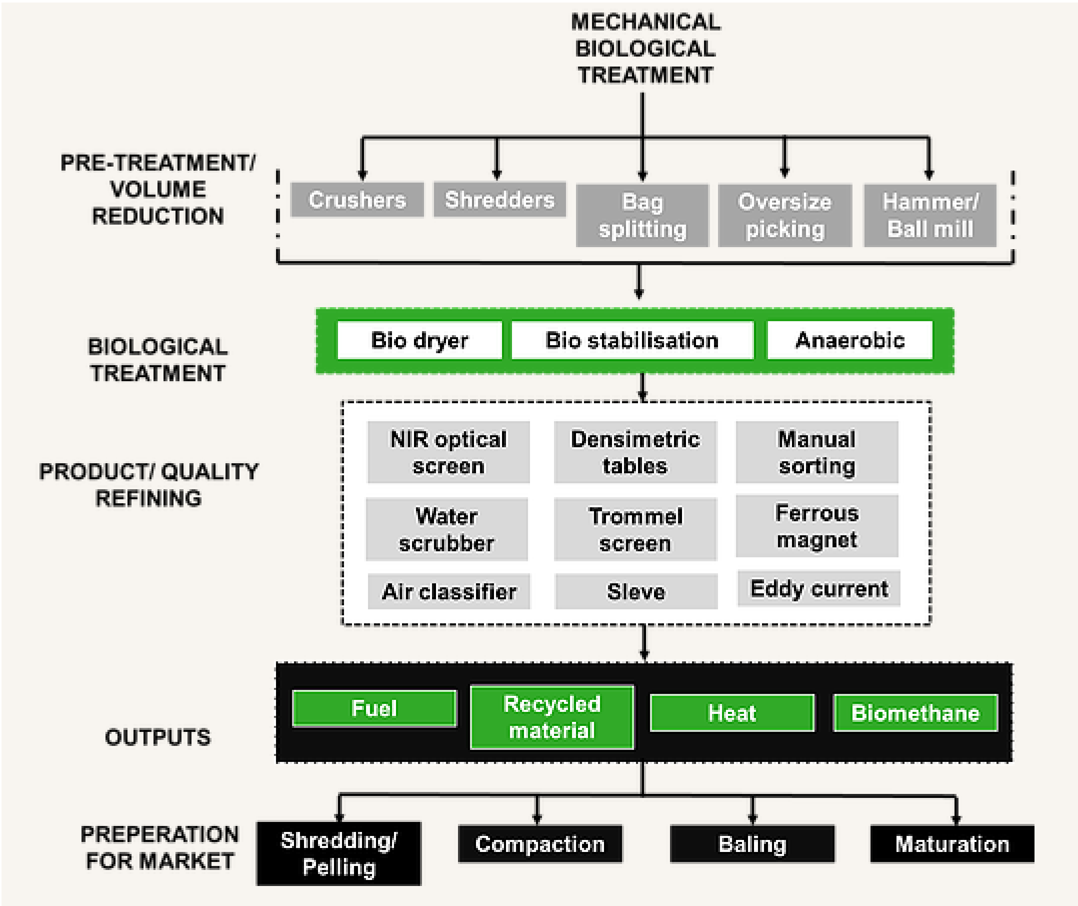


Figure 20: MBT Technology (Source: Environmental Affairs, South African Government)

3.2. Residual Waste Treatment Facility

Residual waste treatment facilities (RWTFs) are specifically designed to separate recyclables from a stream of mixed waste (i.e. residual waste or MSW) without provision to treat and or process the organic-rich fraction found in mixed waste streams. They most often require separate composting or Anaerobic Digestion facilities much like in MRFs. RWTF is

much more similar to MRF in providing an opportunity to recycle at much higher rates than has been and could be demonstrated by kerbside and bring collection systems (ACC, 2015).

The difference, however, is in the type or form of waste being treated. Often times, RWTF is being referred to as ‘dirty’ MRF. Historically, the word ‘dirty’ had been used to emphasize the inherent contamination in mixed waste stream used as feedstock. However, RWTF is a better description of the evolution of these facilities (i.e. dirty MRFs) (ACC, 2015). Much like MRF, RWTF can be designed or configured to accept and process separately collected or co-mingled recyclables as well.

3.3. Combined MBT, MRT and PRT

Plastics recovery facility (PRF) is a facility that takes plastics fractions from material recovery facilities (MRFs) and separates the material by polymer type and/or colour. In practice, upstream pre-treatment operations in both MRFs and PRFs, remove films and non-polymer material such as, for example, metals, papers, glass, and cardboards before reaching the automated sorters. This reduces the mass feed rate through the sorters thus reducing the load through this expensive plant area and potentially reducing operational costs. The difference between these two is in their feedstock and subsequently their output products (WRAP, 2010). The residua waste after source separation not taken to the MRF and PRF can be handled at the MBT plant.

Figure 21: Typical feedstock into MRF (Source: WRAP, 2010)

Figure 22: Typical feedstock into a PRF (Source: WRAP, 2010)

4. EXISTING AND EMERGING PLASTICS SEPARATION TECHNOLOGIES

4.1 Plastics Separation Processes

Plastics separation from mixed wastes, especially, from domestic household waste and/or similar MSW sources could involve up to 3 or more (i.e. mix of preparatory and actual polymer) separation processes before the final plastic recyclates are ready for reuse, reprocessing or conversion. The first separation process would be to separate the dry recyclables such as plastics, metal, glass and paper from the organic-rich fraction of the incoming waste. The resultant dry co-mingled rigid recyclables can then be further sorted into it different component streams using any or combination of automatic and manual sortation methods/techniques.

In the second separation process, automated pre-sorting (usually based on magnetic, density and spectrophotometric properties) can sufficiently separate plastics stream from metals, glass and paper (excluding labels and closures on plastics). The third separation process would involve the separation of the plastics stream into it various different components, usually, PET, HDPE, LDPE, PP and PS present in the mixed household waste originally. Manual hand sorting is considered the fourth separation process with significant potential impact on product purity, which tends to be greater than 95% in most cases.

Manual hand sorting downstream the overall separation process is commonly considered by trained and experienced operators as a good practice and as an integral part of the sorting system (WRAP, 2010). Manual sortation is not an uncommon upstream process in MBT or/and dirty MRF plants as well, often operated through polarized light from Ultraviolet (UV) ray for the separation of PVC from PET. Further separation processes could be deployed when rework is necessary and/or when there is need to improve the quality level of the final plastics recyclates to near virgin plastics quality.

4.2 Plastics Sortation Methods

Separation processes utilize differences in some of the properties of the materials to be separated. The most often used properties to separate plastics are density, wavelength energy, appearance (size and shape), colour, solubility, low temperature behaviour, magnetism, electrostatic charge and melt flow properties. In most cases, however, plastic waste separation from mixed waste utilizes three main properties: electrostatic, density and spectrophotometric (colour, transparency) properties. Traditional magnetic separators sort

and segregate steel metals; eddy current separators sort and segregate non-ferromagnetic metals and spectrophotometric technologies separate waste plastics by colour and polymer types (Villanueva & Eder, 2014). Separation process can be automated or manually carried out or combined in most cases. Figure 23 below represent a schema of available sortation methods.

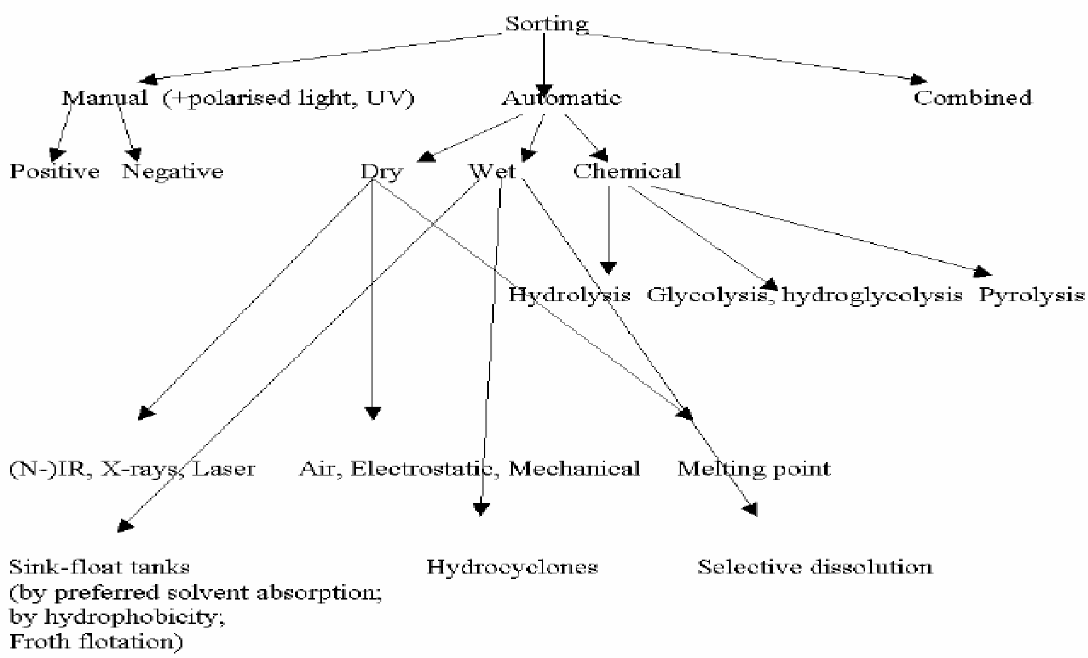


Figure 23: Plastic sortation methods schema (Source: engineering plastic recycling)

It is clear from figure 23 that the two main methods available for plastic waste sortation which are through manual sorting, and using automated systems. Different techniques exist, depending on the variety and/or types of plastics polymers/resins to be segregated for recycling. The technique to be adopted therefore, may be dependent on the type of input material and expected output and the desired/required purity of the output streams. These techniques include dissolution, flotation, cyclones, centrifuges, water table separation, air vibration tables, electrostatics, optical sorting by resin (spectroscopy and x-ray) and by colour (high frequency cameras and visible spectrometer-VIS). For example, piezoelectric methods and high frequency cameras can be used to separate PVC. Elutriation methods are often employed to remove labels and light weight accessories off plastic packaging. NIR sorting is commonly used for the sorting of plastic packaging (Hopewell et al., 2009).

4.3 Plastics Separation Technologies

Having established the fact that separation processes and indeed separation technologies exploit varying properties as mentioned earlier in this chapter; it also worth noting to know and understand the dichotomy involve in the overall separation process when preparing plastic waste for recycling. With regards to the MBT technology discussed in chapter 3; it is clear that residual waste requires initial volume/size reduction and preparatory separation before the actual sorting of materials and/or biological treatment can be achieved. A summary of the different techniques normally employed for this size/volume reduction treatment (i.e. waste preparation) is provided in table 6 below.

4.3.1 Preparatory Separation Technologies

Preparatory (pre-treatment) separation process may involve sub-processes in the initial material sorting process, as may be seen outlined in table 7 (not necessarily in order), such as:

- Manual separation process: - removal of films, cardboard and bulky items
- Size reduction process: - shredding and/or cutting
- Screens, air classifiers and ballistic separation process: - removal of small, light-weight or 2D pieces such as film and paper and heavy pieces such as glass and stones
- Magnetic separation process: - removal of ferrous metals e.g. iron
- Eddy current separation process: - removal of non-ferrous metals e.g. aluminium
- Optical separation of initial materials: - removal of 2D items such as paper and cardboard from 3D items such as containers
- Induction separation process: - removal of metals from plastic stream

The overall goals of these processes are simply to reduce the quantity of non-targeted plastic polymers and recyclable non-plastics such as metals, glass, and other contaminants (e.g. oil, soil, stones, and sometimes dead animals) as well as additives within the plastic matrix. Figure 24 is a generic configuration of an advanced sorting plant for either mono-material collected plastics, co-mingled collected plastics material or dry residual waste.

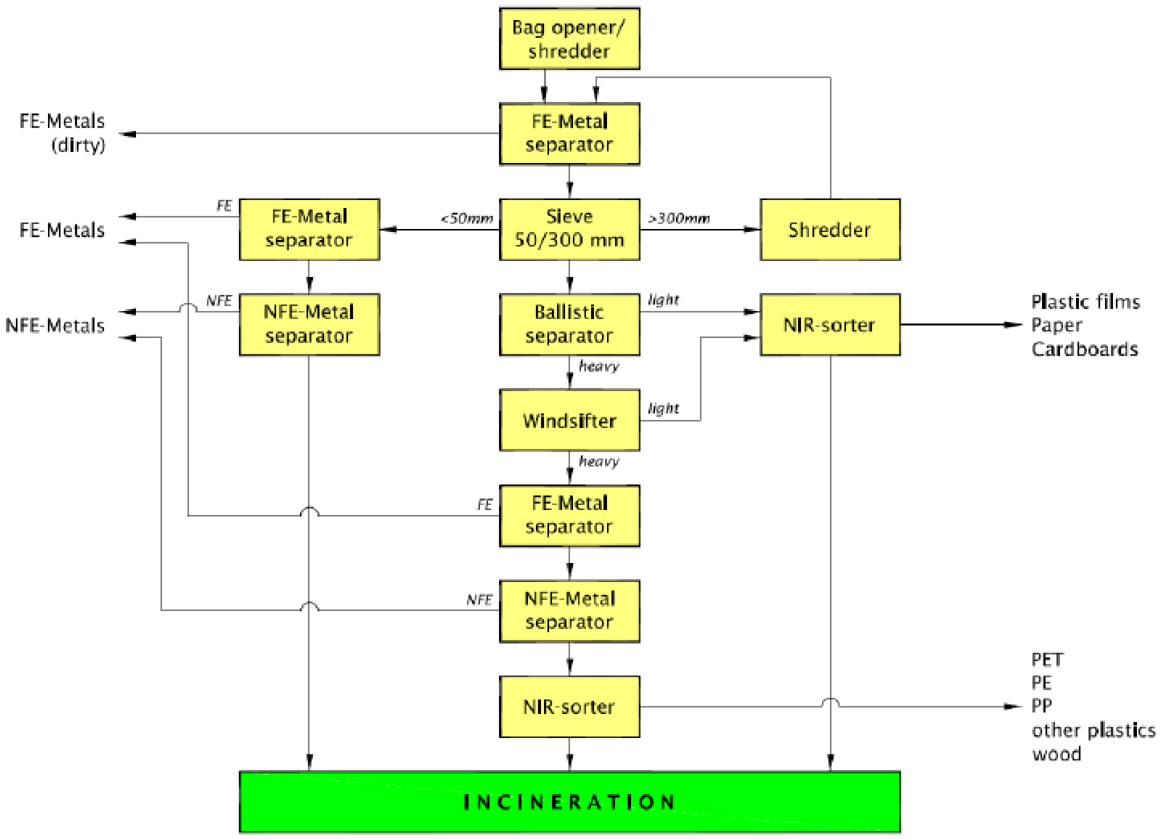


Figure 24: Generic plastic waste stream sorting plant procedure (Source: COWI, 2013)

4.3.2 Polymer Separation Technologies

Polymer separation technologies are predominantly automated sortation technologies usually associated with three core aspects, namely: a conveyor; a feed sensor/regulator and a pneumatic system. Each automated system has a conveyor fitted at it feed-end with a sensor that analyses the materials fed into it. The information from the analysis is sent to a computer system that determines how the material will be sorted. And finally, the pneumatic system segregates materials into the desired streams (WRAP, 2010). The actual polymer sorting process may involve own sub-processes, such as (not necessarily following this order):

- Size reduction process: - shredding or cutting into flakes
- Plastics (polymers) cleaning process: - washing and drying of plastics
- Optical separation of polymers: - removal of polymers by type and colour
- Density separation of polymers: - removal by polymer type

Table 6: Waste size reduction techniques (DEFRA, 2013)

Technique	Principle	Key Concerns
Hammer Mill	Material significantly reduced in size by swinging steel hammers.	Wear on Hammers. Pulverising and 'loss' of glass / aggregates. Exclusion of pressurised containers.
Shredder	Rotating knives or hooks rotate at a slow speed with high torque. The shearing action tears or cuts most materials.	Large, strong objects can physically damage the shredder. Exclusion of pressurised containers.
Rotating Drum	Material is lifted up the sides of a rotating drum and then dropped back into the centre. Uses gravity to tumble, mix, and homogenize the wastes. Dense, abrasive items such as glass or metal will help break down the softer materials, resulting in considerable size reduction of paper and other biodegradable materials.	Gentle action – high moisture of feedstock can be a problem.
Ball Mill	Rotating drum using heavy balls to break up or pulverise the waste.	Wear on balls. Pulverising and 'loss' of glass / aggregates.
Wet Rotating Drum with Knives	Waste is wetted, forming heavy lumps which break against the knives when tumbled in the drum.	Relatively low size reduction. Potential for damage from large contraries.
Bag Splitter	A relatively gentle shredder used to split plastic bags whilst leaving the majority of the waste intact.	Not size reduction. May be damaged by large strong objects.

Table 7: Waste separation options (DEFRA, 2013)

Separation Technique	Separation Property	Materials targeted	Key Concerns
Trommels and Screens	Size	Oversize – paper, plastic Small – organics, glass, fines	Air containment and cleaning
Manual Separation	Visual examination	Plastics, contaminants, oversize	Ethics of role, Health & Safety issues
Magnetic Separation	Magnetic Properties	Ferrous metals	Proven technique
Eddy Current Separation	Electrical Conductivity	Non-ferrous metals	Proven technique
Wet Separation Technology	Differential Densities	Plastics, organics will float Stones, glass will sink	Produces wet waste streams
Air Classification	Weight	Light – plastics, paper Heavy – stones, glass	Air cleaning
Ballistic Separation	Density and Elasticity	Light – plastics, paper Heavy – stones, glass	Rates of throughput
Optical Separation	Diffraction	Specific plastic polymers	Rates of throughput

Exclusively specific to polymer separation are optical, density and electrostatic separation techniques, depending on the input material and desired output stream and its purity and quality levels requirements. Polymer sorting/separation technologies encompass a wide range of possibilities including state-of-the-art and advanced technologies such as:

- Sink-float (S/F)
- Flotation (FLOT)
- Hydrocyclone (CYCL) & centrifugal
- Triboelectrostatic & electrostatic (E-STAT)
- Mid infrared (MIR) thermography
- Colour analysis/visible sorting (VIS)
- Near infrared (NIR)
- X-ray transmission (XRT) imaging
- Energy dispersive X-ray fluorescence (XRF)
- Raman spectroscopy (RAMAN)

- Laser fluorescence
- Laser induced Plasma/Breakdown spectroscopy (LIBS/LIPS)
- Mid infrared (MIR) spectroscopy
- Magnetic density separation (MDS)
- Terahertz spectroscopy (Tera Hz)
- CREASOLV® (a selective dissolution technology)
- Polymer tracing (TRACER) (Frerejean et al, 2014).

4.3.3. Preconditions Requirements

There are usually preconditions requirements to be fulfilled especially since input materials are often mixed MSW which may also be co-mingled recyclable packaging waste. A major general requirement is the splitting of incoming waste into, for example, three fractions, namely:

- Undersize: < 50 mm
- Middle size: 50/300 mm
- Oversize: > 300 mm

This makes size/volume reduction or separation process the first primary sorting process after bag opening or shredding. Shredding, however, may not always be necessary. Plastics are usually found in the middle size and oversize fractions. Both 2D and 3D middle sized fractions are further sorted in a ballistic separator and or air classifier. The oversized fractions are handpicked via manual sorting of large 2D plastic films.

More specific preconditions as applied to the already enumeration polymer separation technologies can be found in table 9 of section 4.4.

4.3.4. Density Separation of Polymers

Today's density separation technologies often employed for sorting plastics with fluid medium (i.e. wet technologies) are: Float-sink, Hydrocyclone/Centrifugal and Flotation technologies. These technologies are not only similar from view point of operating principle, but are also among the matured, well-established, existing, commercially and industrially available technologies in the plastic waste management industry (Frerejean et al, 2014).

In sink-float separation, plastics sorting can be achieved in a fluid with density in-between the polymers/resins types making it possible for less dense materials to float and the heavier to sink. Hydrocyclone separator uses the principle of centrifugal acceleration to separate polymer mixtures into a heavy and a lightweight fraction on the basis of their specific density. The presence of water slurry in which the material to be separated is submerged

makes the cyclone hydro. It is actually a centrifugal separator with a fixed wall. Flotation causes the separation of polymer mixtures by inducing hydrophilic polymers to sink and hydrophobic ones to float. Details and further reading of these technologies and other automated sorting technologies can be found in REMIX-an interim report on benchmarking of existing and emerging technologies for sorting and recycling of mixed plastics waste by Frerejean et al (2014).

A sample of density properties of different polymers and their floatability in different solution media usually utilized in density separation technologies is as seen in table 8 below.

Table 8: Floatability Sample of plastics in various solution media (source: Siena Green Chemistry Summer Institute)

Plastic	Plastic Number	Alcohol Solution 0.9 grams/cm^3	Water solution 1.0 grams/cm^3	NaCl Solution 1.1 grams/cm^3	$CaCl_2$ Solution 1.3 grams/cm^3	Literature value for plastic density grams/cm^3
PETE Polyethylene Terephthalate	1	sink	sink	sink	float	1.31
HDPE High-density Polyethylene	2	sink	float	float	float	0.96
V Poly Vinyl Chloride	3	sink	sink	sink	sink	1.4
LDPE Low-density Polyethylene	4	sink	float	float	float	0.88
PP Polypropylene	5	float	float	float	float	0.86
PS Polystyrene	6	sink	sink	float	float	1.05

4.3.5. Optical Separation of Polymers

Optical separation of polymers is generally employed to sort plastics by resin and colour recognition. Sorting plastics by resin can be achieved by utilizing spectroscopy and x-ray. Spectroscopy unit emits light and each type of plastics reflects the light with a unique signature, or wavelength. A sensor reads the signature and the processing units decides how the plastic should be sorted. Examples of spectroscopy technologies as earlier mentioned in the polymer separation technologies section of this chapter are: Raman, Laser, Mid-range infrared, Fourier-transform near infrared (FT-NIR) and Terahertz spectroscopy.

X-ray units, including both conventional x-ray and x-ray fluorescence (XRF), look at plastics on an elemental level and use secondary (fluorescent) x-rays to analyse material. This technology is especially useful in detecting elements such as chloride (PVC) and bromine

additives, such as the brominated flame retardants, often found in plastics used in electronics (ACC, 2011).

Sorting by colour recognition can be achieved by using vision technology which uses camera systems, such as CCD linear cameras, to sort streams into clear and coloured fractions; and spectroscopy (especially NIR), including visible range spectrometer (VIS) for polymer type analysis. These optical sorters can be used to differentiate between clear, light blue, dark blue, green and other colours PET containers.

4R Sustainability Inc. showed in its report conducted for the American Chemistry Council some remarkable and interesting whole unit and flake/size-reduced optical plastic sorting equipment. The flake and size-reduced plastic sorting equipment manufacturers, 14 in number, offered 27 different units that sort shredded plastics (including plastics commonly referred to as plastic flake), as well as size-reduced non-bottle rigid plastics such as plastics from WEEE. In the same report, 13 manufacturers offered 27 different units that sorts whole plastic containers. Two of those units were singulated feed, in which containers were detected through the sensor individually, the rest were mass-feed system. Tables showing this information based on such performance criteria as the basis of technology, primary application, resins identification, colours sortation, throughput, accuracy, and upgrades and optional features can be seen or found in appendix C.

4.4 Summary Synthesis for Plastics Separation Technologies

Table 9 is a synthesis summary of existing and emerging polymer separation technologies in terms of their capability, capacity, advantages and disadvantages.

4.5 Plastics Separation Technologies Ranking

Based on a normalized 50-50 weighting of both general and technical performance criteria, Frerejean et al. (2014) generated an insight into the ranking of plastics separation technologies (as can be seen in figure 25, 26 and 27) on the basis of mixed plastic waste packaging, WEEE and ELV streams. Five criteria each were considered for technical and general performance.

Table 9: Main strengths and weaknesses of sorting technologies (Frerejean et al., 2014)

Technologies	Weakness	Strengh	Remarks
Sink and Float (S/F)	-Slow -Poor when polymers have the same range of density -Needs salts in the water and wetting agent -Density of the water solution hard to control -Needs water treatment -Drying materials after separation mandatory -Needs a "constant" granulometry	-Simple and improved method -Easy after wet grinding operation (no need to dry before sorting) -Able to sort whatever the color	The evolution of polymers with fillers, blends, decrease the accuracy of this technology
Hydrocyclone (CYCL)	-Needs water treatment -Needs specific equipments which increase the cost -Drying materials after separation mandatory	-Allows the separation of materials with small density gap -No limitation with colors -High volume -Less sensitive to size particles dispersion than S/F	The commercial development of this technology not really effective
Flotation (FLOT)	-Needs different kind of froth agent, pH modifier and other chemical reactives -Needs a permanent control of the bath properties -Size of the wastes needs to be small	-more than 98% of purity -No limitation with colours -Easy to change the separation parameters -is also potentially very sensitive to small differences in material density	Complementary to S/F technology
Triboelectric and electrostatic sorting techniques (E-STAT)	-Materials need to be very Dry -only on small particles without dust -Only for binary mixtures	-Improved continuous technology -Dry process -No needs of additives -High volume (2T/h) -Purity up to 99,5%	

Visible (VIS)	-Cannot sort polymers per molecules type -The size range of products to sort needs to be the same	-Improved technology -Very high capacity (up to 10T/h) -high purity -A lot of applications in PET bottle to bottle	
XRT	-Do not allow to sort flame retardant by different molecules -Need same range of particle size	-Recognize substances with high weight atomous (Cl, Br, Pb…) -No limitation with the coulours	-Lots of application to sort different metals
XRF	-New in continuous applications for sorting wastes, so needs more developments	-Allow precise heavy substances amount measurement	-Lots of application to sort different metals
NIR Spectro	-Not available for Brominates Flame Retardant detection -Doesn't allows mesurement of carbon black dark plastics	-Allows to sort polymers by type -Allows to sort polymers, papers and wood in a mixed stream	
MIR Spectro	-Slow acquisition and treatment technology, not yet available for continuous sorting	-allows to sort polymers with no color limitation.	
MIR-Thermographie	-Needs an important source of heat - Good development perspectives	-will probably allow to make improvements in sorting of black plastics, mix of polymer and plastics with BrFR	-Provide improvments in the sorting of papers and cardboard
RAMAN Spectro + laser Fluorescence	-Very expensive technology - Not yett mature on WEEE neither ELV	-Allow fast identification of molecular structures /NIR -Can sort regardless to the colour (Black OK) -No need to clean or dry before sorting -From literature seems, able to detect BrFR	A Japanies systems from Saimu Corp. seems to be at evaluation stage-A german one from UNISENSOR is at industrial stage for PET flakes bottle to bottle sorting and under evaluation for WEEE, but not able to detect BrFR.
LIBS	-The time of measure is the main limitation of this promising technology	-Allows to recognise light atoms (/XRT) and BrFR (NIR) -Allows to make the difference between different types of BrFR	Pellenc is working on sensors to identify black plastics

TERA HZ Spectro	-Development of emission source difficult (quantum cascade Laser needs very low temperature)	-Allows precise molecular structure evaluation -could be of a great help to sort black plastics	TeTechS Inc. has patented pending technology
MDS (S/F)	-Needs water treatment -Needs a specific system to recover nanoparticles	-Very sensitive to small differences in material density (0,02 kg/m^3) -cheap because it separates a complex mixture into 5 different fractions in a single process step, using one and the same liquid	
CREASOLV Dissolution technology	-Needs solvent regeneration and treatment	-Allows to separate polymers per family -Allows to recover BrFR molecules	
TRACER	-Needs a specific and comon legislation (EU or Worldwide) -Tracers rare earths are expensive	-Well adapted to solve problems of shredded dark polymers	Industrial application will take time, to which we have to add the necessary time for material end of life (10 years for vehicles)

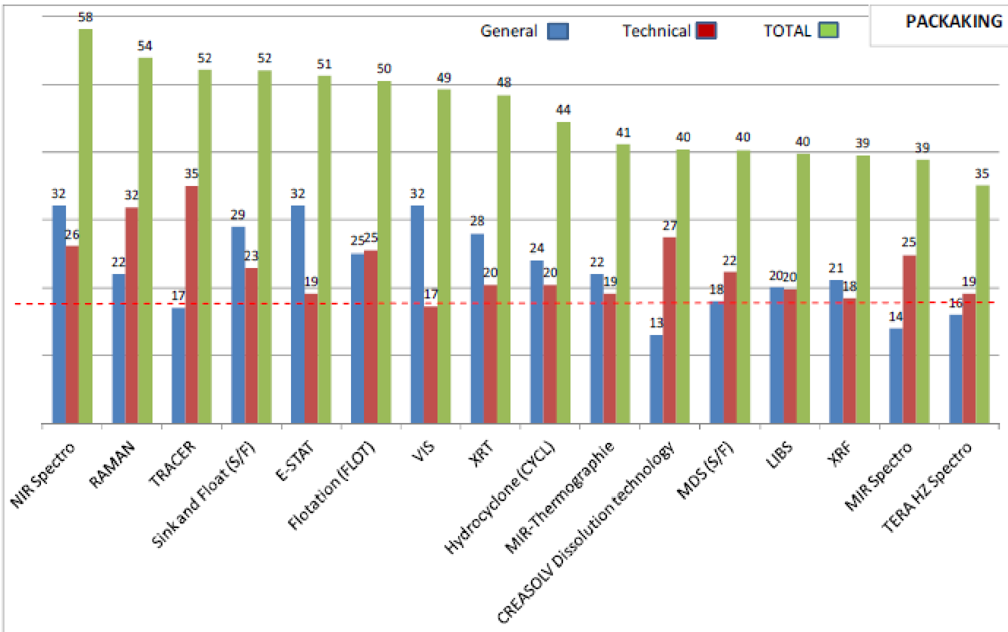


Figure 25: General and technical ranking of sorting technologies for plastic packaging stream

The considered criteria are:

- Technical
    - Yield
    - Polymer identification
    - Sorting of chlorinated components mainly PVC
    - Sorting of black plastics
    - Sorting of Brominates Flame Retardant (BFR)
- General
    - Economic viability
    - Maturity
    - Implementability
    - Respect of environment
    - Safety

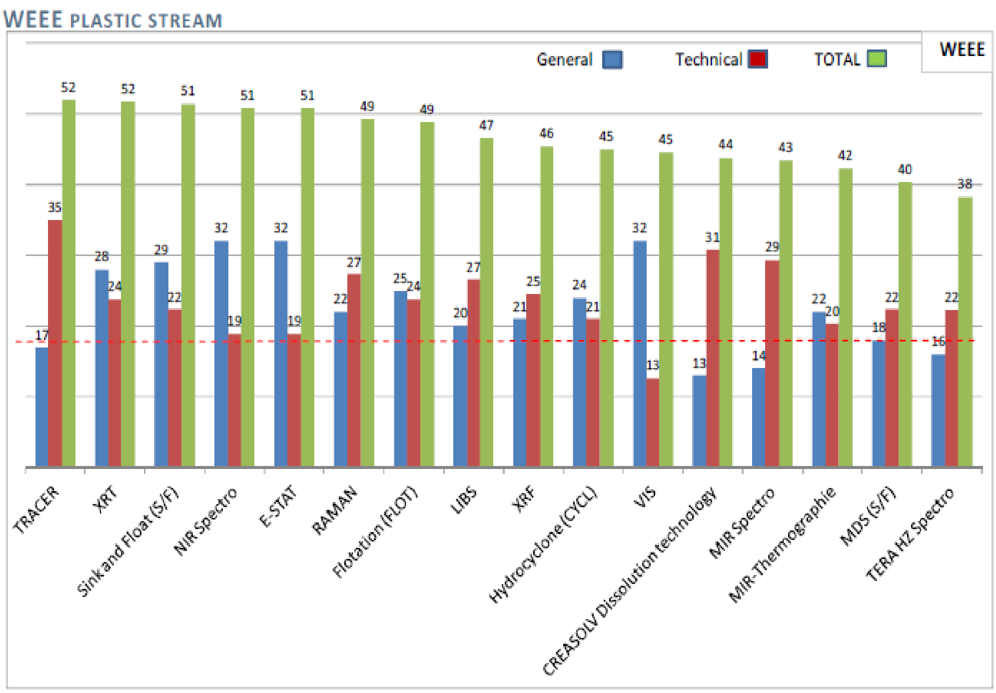


Figure 26: General and technical ranking of sorting technologies for WEEE stream

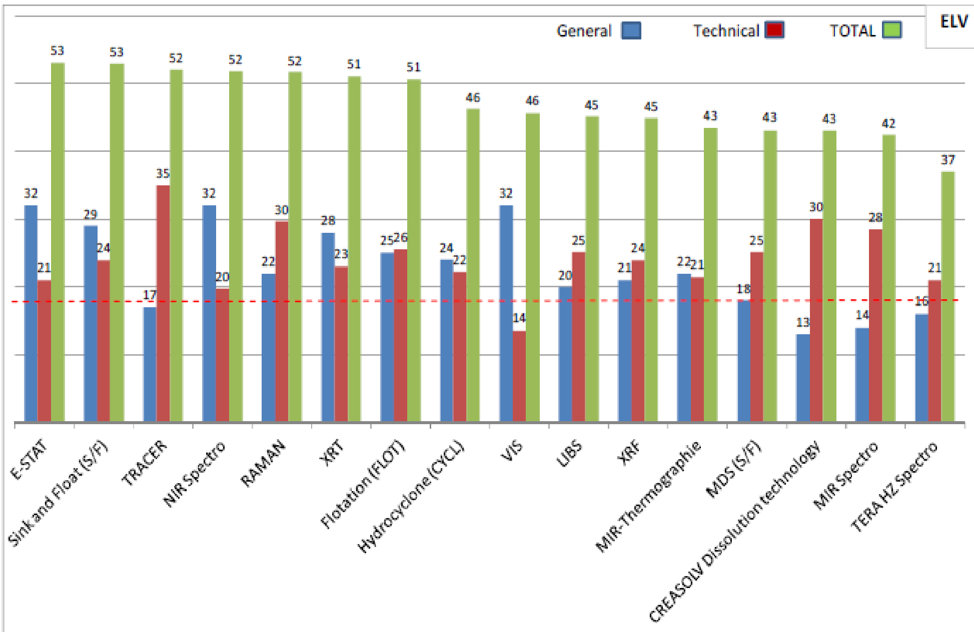


Figure 27: General and technical ranking of sorting technologies for ELV stream

4.6 Plastics Separation Technologies Ranking Conclusions

Apparently, at the top of these available separation technologies are seated 5 topmost technologies, namely: S/F, NIR, E-Stat, XRT and RAMAN. The first three are matured; they have a history of existence and are widely implemented, but failed to completely address all recycling problematic. XRT and RAMAN are emerging with rapid growth in WEEE and packaging respectively; with attendant improvement, over existing technologies used for the same purpose. MDS and CREASOLV technologies are also emerging but seem set only for specific applications; CREASOLV in the recovery of BFR-containing WEEE and MDS in packaging.

A look into the technical aspect revealed some other technologies such as MIR Spectro and LIBS with good potentials mainly specific to WEEE and ELV problematic resolution. However, these technologies are yet to come to maturity let alone find industrial application. Although RAMAN technology seems able to significantly increase the recycling yield of PET “bottle to bottle” stream and has ability to separate a wide range of polymer types at the same time, it has only a few industrial applications because of its present expensive offer and being limited to just one supplier in EU at the moment. The implication is that if there is an increase in the share of black plastics present in EU household plastic packaging waste and the price of RAMAN remains high, then a cheaper and much less expensive alternative technology capable of sorting black plastics and a wide range of polymer has to be

developed, otherwise the pricing issues of RAMAN has to be resolved to make it readily available on a commercial basis.

4.6.1 Conclusion on Packaging

In household plastic packaging sorting, the above ranking suggests that polymer identification and sortation performance are the most important criteria. This is followed by ability to sort PVC which could cross-contaminant other polymer streams. The ability to sort black plastics is not of much significance since the share of black plastics in household packaging are usually very minimal. Brominated Flame Retardant (BFR) is not a problem either as such chemical compound are usually absence in household packaging.

Consequently, the utilization of NIR and NIR + VIS in the separation of different polymers present in packaging plastic waste and the elimination of PVC films on PET, as well as the recovery of PET for bottle to bottle application has been seen as the biggest industrial success story of packaging recycling (Frerejean, 2014). NIR + VIS is rapidly replacing manual hand sorting upstream of the entire separation process. For example, a high performing and well configured NIR systems can achieve in excess of 80% yield and 95% purity. Complementing this with manual hand sorting the purity can be raised up to 99.99%. However, RAMAN + Laser fluorescence seems a potential alternative to NIR with added ability to detect black plastics with higher performance accuracy, and large-scale volume sorting.

In most cases, depending on the geographical area of collection, the diverse nature of plastic packaging waste stream could vary from streams solely or mainly composed of rigid bottles (i.e. PET and PE) to streams composed of additional trays, toys, furniture, films and pots, with a wide range of polymers. This makes proposing a unique technological solution to the recycling of household packaging waste unlikely.

4.6.2 Conclusion on WEEE

In WEEE sortation, the most significant criterion, majorly to increase and improve the current recycling rate, is the sorting of black plastics. This is followed by sorting of BFR, polymer identification and yield, in that order. The sorting of PVC is the least important. The current more matured and developed technologies in use for WEEE sortation is the combination of S/F and Flotation, as well as S/F and electrostatic separation. These technologies use are based on the increase of density with BFR additives. For example, S/F and electrostatic allow the separation of PP from ABS and PS; and then separate ABS from

PS. Similarly, S/F and flotation allow separation with more sensitivity PP, PP filled with Talc, PE and ABS with 97% of purity.

There are however emerging technologies set to significantly improved upon the deficiencies associated with the more developed existing WEEE sortation technologies. According to Frerejean (2014), one of such technologies is UNISORT GmbH, based on RAMAN and Laser fluorescence. It seems able to separate several polymer types out of a mixed input stream of shredded plastics, automatically, with a high throughput rate of approximately 1 ton per hour. It potentiality to identify and sort black and dark plastics might endear it to become a key technology to transform BFR free plastic shred from WEEE into marketable sorted polymer type fractions, which is otherwise impossible with NIR technology. Other promising technologies in this aspect are XRT, LIBS, XRF and CREASOLV.

4.6.3 Conclusion on ELV

ELV sortation criteria is quite similar as for WEEE, except for BFR, which is less important in this case because of few application with flame retardant in ELV rigid plastics. If present at all, they are mainly concentrated in PUR foam of the seats which is not mechanically recyclable. Due to the nature of ELV not really being a mixed plastic stream but mainly PP or PP copolymer (i.e. PP-EPDM), it existing matured choice separation technologies in order of preference are E-STAT, S/F and NIR.

There are however emergent technologies in this area which have shown high potentials for detecting and identifying fillers present in polymers. For example, XRF could identify fillers but not the nature of the plastic; MIR could greatly improve the identification of fillers but it is yet to enter into the industrial stage. XRT appears the most efficient and matured emerging technology at the moment to remove PVC. Technically, TRACER technologies seem the best way to recover each polymer not only for ELV stream but also for packaging and WEEE. Generally, however, the way to achieve this appears difficult and impracticable, at least in short and middle terms.

4.7 Separation Efficiency

Separation efficiency may be considered as either technology or process efficiency depending on which is applicable at a given instance. As earlier discussed in this chapter, each separation process utilizes different sortation techniques and/or methods involving the use of several separation technologies. In other words, in order to achieve a specific or single polymer stream product output from a comingled or mixed waste stream via a separation

process, several separation technologies had to be considered to achieve utmost purity and yield (throughput) levels. In either case, the yield and purity levels had to be used in conjunction with each other to obtain the separation efficiency. Furthermore, a unit or process product purity, yield and separation efficiency tends to provide an overall assessment of a sortation performance.

An understanding of yield and purity is important when considering the product/output fraction of a target material such as any of the already mentioned polymer types. It is possible to have high yield and low purity; low yield and high purity; and high yield and high product purity at different instances. For example, utilizing NIR technology at an instance, a low purity and high yield may suggest an incorrect ejection of non-target material into the product stream by the NIR sorter. Conversely, a low yield and high purity may indicate that the NIR sorter has not been able to identify all of the target material; thus, allowing them to pass unejected into the product stream. A high yield and high purity is an indication that the target material has been correctly identified and ejected while minimizing the ejection of any non-target material (WRAP, 2010).

4.7.1 Polymer Separation Technology Efficiency

Polymer separation technology (i.e. a unit) efficiency is a measure of how effective a sortation technology such as NIR, RAMAN, XRT, is, at sorting. It may be defined as the probability of the target material being correctly separated into the desired product stream by the polymer sorter. Mathematically, this may be expressed as:

$$Separation\ efficiency = \frac{Quantity\ of\ target\ material\ in\ product\ (weight)}{Quantity\ of\ target\ material\ fed\ into\ sorter\ (weight)}$$

Usually, values above 90% are considered very good; 80-90% as good; 70-80% acceptable; whilst below 70% is an indication of poor separation. In contrast, 70% of process efficiency may be considered efficient and a good separation operation. Whilst between 75-85% are considered very efficient and very good; it is fairly unlikely to achieve a process efficiency greater than 85% in recycling/recovery plants.

Given a unit sorter (e.g. NIR) configured to positively sort and remove 2.5 tonnes of HDPE with a purity level of 96% off the 3 tonnes of HDPE present in the 10 tonnes of mixed plastics feed through the unit. For instance, important parameters such as purity, yield and separation efficiency can be deduced and evaluated as

follows:

$Purity\ is\ the\ \%\ of\ target\ product\ within\ a\ product\ fraction: thus, the\ compositional\ analysis\ of\ HDPE\ product\ fraction\ shows\ it\ contains\ 96\%\ HDPE\ by\ weight, thus\ the\ purity\ is\ described\ as\ being\ 96\%.$

$Yield\ is\ the\ \%\ of\ material\ recovered\ from\ the\ feed\ stream\ to\ the\ target\ product\ stream$

$$Yield\ (\%) = \frac{Quantity\ of\ product\ produced}{Quantity\ of\ product\ material\ in\ feed\ fraction}$$

$$Yield\ (\%) = \frac{2.5}{3} = 0.8333333$$

$$Yield \approx 83\%$$

$$Separation\ efficiency = purity * yield$$

$$Separation\ efficiency = 0.96 * 0.83$$

$$separation\ technology\ (i.e. unit)\ efficiency \approx 80\%$$

Alternatively, this can also be calculated as:

$$Quantity\ of\ target\ material\ in\ product = Configured\ throughput\ (yield) * purity$$

$$Quantity\ of\ target\ material\ in\ product = 2.5 * 0.96 = 2.4\ tonnes$$

$thus$:

$$Separation\ efficiency = \frac{Quantity\ of\ target\ material\ in\ product\ (weight)}{Quantity\ of\ target\ material\ fed\ into\ sorter\ (weight)}$$

$$Separation\ efficiency = \frac{2.4}{3} = 80\%$$

4.7.2 Plastic Separation Process Efficiency

Since separation process usually may include consortium of individual separation units or technologies; it may be impractical in most cases to measure the separation efficiency of individual sorting unit in existing processing (i.e. MBT, PRF and MRF) plants. These plants and/or facilities are far more likely to measure and record data across the full separation process from in-feed to bunkers downstream of the sorters. In this case and instances, so many sorters are likely to be involved in which the separation efficiency and product purity

across each unit should be monitored and measured regularly to ensure overall separation performance and quality are maintained.

Processing plant separation efficiency is the concern here and not unit separation efficiency. Consequently, a significant operational metric or tool, key to the determination of the overall separation efficiency and performance has to be defined. This major key performance indicator (KPI) is known as the Overall Equipment Effectiveness (OEE). OEE relates to measuring purity level (quality rate), and yield level (performance/capacity rate) during process running time. It simply helps visualise automated and processing systems performance.

GBB study revealed and reiterated that many of the current mixed waste processing facilities with optical units are claiming recovery rates in excess of 80%. GBB however, suggested that a more conservative approach of total plastics packaging recovery could be in the 50-60% range. Stating that this assumption would be a significant recovery number in terms of value and total recovery percentage since there is presently little to no public data to substantiate the greater than 80% claims (ACC, 2015). In other words, and according to Mike James (2010), reporting efficiency (i.e. unit/technology efficiency) of 85-90 % may actually reflect as 40-60% OEE (i.e. process efficiency).

Theoretically, OEE is separation efficiency (i.e. process separation efficiency) with the inclusion of process running time. OEE can be expressed mathematically as:

$$OEE = performance\ (capacity\ rate) * quality\ rate * availability$$

$$Performance\ (\%) = \frac{actual\ measured\ throughput}{rated\ throughput}$$

$$Quality\ rate\ (\%) = \%\ of\ product\ meeting\ the\ product\ specification$$

$$Availability\ (\%) = \frac{actual\ plant\ running\ hours}{planned\ plant\ running\ hours}$$

OEE is especially suited for all operational separation processes involved in the entire process at MRF, PRF and MBT plants; particularly in cases where it is not possible to measure one process independently from the rest of the process. OEE can be calculated for a single separation process whenever possible.

Capacity rate is the only metric that is directly related to process machines’ efficiency. It can allow a facility to compare availability downtime with efficiency. In other word, it is often

also referred to as performance metric. When measured, it can reveal specific faulty line and or machine having efficiency issues rather than operator issues (James, 2010).

It is also worth noting that the quality rate metric applies to the overall separation process including any manual hand sorting after the final polymer sorter and is not ascribed to individual sorter. Consequently, manual hand sorting, conducted after the final process sorter, as part of the normal operating process is not considered to be a rework or reprocess operation but as part of quality rate metric (WRAP, 2010).

Setting of benchmarks for each component of OEE is required as it is essential for recycling facilities to have a point of reference for determining when these components meet or do not meet acceptable levels. For instance, in order to achieve a separation efficiency of 80% as seen in the example in section 4.7.1, availability will have to be 100%. Obviously, this is usually not the case, as there always exist disparity between actual operating time and planned time. Consequently, with an availability of 50-75%, an OEE of 40-60% can be realized in this case.

That is, with availability of 50%, separation process efficiency becomes:

$$OEE = performance(yield/capacity\, rate) * quality\ (purity)\ rate * availabilty$$

$$OEE = 0.83 * 0.96 * 0.5 = 0.3984$$

$$\therefore Separation\, process\ efficiency \approx 40\%$$

Similarly, a 75% availability will produce:

$$OEE = 0.83 * 0.96 * 0.75 = 0.5976$$

$$\therefore Separation\, process\ efficiency \approx 60\%$$

This OEE range is considered common and typical of processing and manufacturing companies just starting to track and improve their manufacturing processes performance and downtime with substantial potential for improvement. Addressing the largest sources of downtime, one at a time, could help bring the overall process efficiency to near perfect (100%) and or world class (85%) category (Vorne, 2016).

5. FINLAND: A CASE STUDY

5.1. Background

Finland is apparently well developed in the transformation of waste into energy and has yet to develop and show its capability in recycling, particularly in regards to waste plastics, unto its full potential. Its plastic waste recycling rate has remained perpetually below the 30% mark. It was estimated, for example, at 17.7% in 2010 while energy recovery stood at 44.7% in the same year (European Commission, 2014).

In more recent years (i.e. 2014), and according to available data, it has been estimated to be about 20%. These rates are inclusive of all post-consumer plastic waste involving both mechanical and feedstock recycling. However, waste plastic packaging recycling rate has been on the increase, thanks to the producer responsibility and source separation schemes in force. The recycling rate of plastic packaging (predominantly, PET bottles), for instance, in 2014, stands at around 24 % (PlasticsEurope, 2015a); RINKI reported 25% (RINKI, 2016).

Notwithstanding, these facts underscore the main reason why Finland has been chosen for this case study evaluation with a view to see how separation technologies could help step-up the recycling rate of plastic waste in order to keep up with the EU plastic packaging target of 45% in 2020; 60% in 2025 and also make Finland a truly circular economy as well as a truly recycling society it aspired to be.

Finland has been known and/or seen to meet the minimum target requirement of the plastic packaging directive and national target beginning from 2008 to date, according to EUROSTAT (2013) and RINKI (2016) reports (see *appendix B*). And now, it is time for less focus on plastic packaging waste in favour of focus on total plastic waste as well as less of plastic waste being recovered as energy in favour of plastics material recovery. The era of Waste-to-Resources (WTR) has finally come!

5.2. Waste Plastic Stance and Scope

Finland separately collect plastic packaging waste (excluding PET bottles) for energy recovery as fuel of high calorific value from MSW. It jointly operates deposit return system with Åland in the form of bring back system for PET. Whereas bring systems are the most common means for separate collection of plastic packaging waste (especially PET bottles) from MSW sources in some neighbouring Nordic countries such as Sweden, Denmark, and Iceland, unlike in Norway where kerbside collection is dominant for the same purpose (Norden, 2014).

Finland operates a legal form of producer responsibility; Norway operates voluntary form of producer responsibility and Denmark has no producer responsibility scheme for the implementation of the EU packaging directive. Packaging and non-packaging plastic waste are collected and treated together, whereas rigid (dense) and flexible (film) plastic packaging waste are separately collected (Norden, 2014).

There is no dedicated nationwide collection and recycling systems in Finland at the moment for bulky plastic waste and non-packaging small plastic waste items. Non-packaging small plastic waste are usually left in the mixed waste and sent to energy recovery or landfill. However, some non-packaging small plastic items that unintentionally follow plastic packaging waste stream could be subjected to recycling if the polymer type matches with the polymer being sorted in the sorting process.

Rigid plastic packaging waste materials are commonly recycled into plastic products such as conduit pipes, flower pots and cups, garden walls, chairs and benches, and not back into plastic packaging items. Whereas, flexible plastic packaging waste materials are almost always recycled back into packaging in the form of plastic bags. On the other hand, PET bottles are often always subject to 'bottle-to-bottle' recycling. Apparently, in matters regarding plastic packaging recycling, Finland has chosen not to surpass the minimum requirements in the PPWD (i.e. 22.5%).

In Finland, as is in some other Nordic countries such as Denmark, PET bottles are included in the separately collected amounts; whereas in Sweden and in Norway, this is not so. This inclusion in Finland, is significant and makes an important difference, as hardly any plastic packaging from households apart from PET bottles is subject to recycling until recently (atleast about a year ago from the time of writing this paper) (Norden, 2014). Data for PET bottles ultimately comes from PALPA. An overall average of 12 PET bottles are returned every second, aside those recovered from MSW. In a year, it amounts to about 350 million returned bottles. The returning rate of plastic bottles is around 93% (PALPA, 2014). For Finnish plastic packaging waste specifications, see *appendix C*.

Bulky plastic waste generated by Finnish households are often taken care of at manned recycling centres, and are subject to recycling if considered recyclable by personnel, otherwise, to energy recovery. To a larger degree, at least 95% of source separated/sorted plastic packaging are not subjected to recycling, but to energy recovery until recently.

Plastic packaging put on the Finnish market is the registered amounts in RINKI system. Separately collected plastic waste from households constitute a mix of plastic packaging and non-packaging small plastic wastes. Subsequently, recycling of plastic packaging has been defined as: *separately collected amounts sent to recycling (not recycled yet) divided by amount of plastic packaging put on the market by registered producers* (Norden, 2014). It is however worthy of note that this definition excludes the "final recycling process." This according to the newly proposed waste recycling definition by the European Commission in its Circular Economy waste proposal, means: *the recycling process which begins when no further mechanical sorting operation is needed and waste materials enter a production process and are effectively reprocessed into products, materials, or substances* (Eurometaux, 2016; PlasticsEurope, 2014).

In all Nordic countries (including Finland), central sorting/separation of MSW or mixed residual waste (at MWPF) to derive plastic packaging waste and other recyclable fractions is not a common practice. However, Fortum (formerly Ekokem) can be cited as one company that is involved in mechanical separation of plastic packaging waste from MSW in its RWTF at its circular economy village in Finland.

5.3. Legislative Aspect and Scope

The two key waste legislations to which Finland is subscribed as an EU member state and upon which the larger part of its national waste management programs are based, are Packaging and Packaging Waste Directive (PPWD) and the Waste Framework Directive (WFD). The very first comprehensive piece of EU legislation on PPWD came into force in 1994 (94/62/EC). This was later reviewed in 2004 (2004/12/EC) and in 2005 (2005/20/EC). The later review was carried out in order to give new EU Member States (MS) transitional periods to attain recovery and recycling targets. In 2012, Directive 2013/2/EC was adopted specifically for the amendment of Annex 1 of PPWD on illustrative examples of packaging (Expra, 2016).

The aim of PPWD was to contribute to the reduction of negative impact of packaging and packaging waste on the environment and to ensure the well-being of the internal market directly involved. Consequently, a system of collection and recovery of packaging attainable through recycling and recovery targets setting was introduced. The 2004 Directive minimum plastic recycling rate stands at 22.5%. Interestingly, Finland and nearly all EU member states

and all Nordic countries have no specific targets for the collection and recycling of plastics other than for plastic packaging (Norden, 2014).

The EU's WFD (2008/98/EC) help define key concepts such as waste (outside packaging) and recycling as well as lays down key waste management principles including End-of-Waste criteria, Waste Hierarchy, and Extended Producer Responsibility (EPR). WFD also includes provisions for setting up waste management plans and waste prevention programs (Expra, 2016).

And yet another key game changer and driver, is the landfill ban (due to methane production) on all waste containing substantial amount of organic or digestible waste such as food and/or nutrient waste; particularly waste containing more than 10% TOC (total organic carbon). Legislation however categorise organic as meaning chemically organic materials such as hydrocarbon compounds which also includes plastics, wood, paper and cardboard.

5.4. Key Authorities in the Collection and Recycling of Plastic Packaging Waste

In Finland, as of the time of writing this report, RINKI Ltd (formerly PYR-The Environmental Register of, Packaging) is in charge of the Finnish Packing Recycling activities and the relevant extended activities leading to the name change in 2015. Recalled that it was originally established in 1997 and owned by Finnish industry and retail trade. It was established to provide efficient, sustainable solutions to enable firms comply with producer responsibility (PR) for packaging. According to RINKI, it is building a network of eco take-back points for consumer packaging waste for the collection of packaging and for the recycling of plastic packaging and other recyclable packaging. It claims that there are 1,850 RINKI eco take-back points, 500 of which also accept plastic packaging and that the collection had commence in January 2016.

Suomen Palautuspakkaus Oy (presently PALPA) manages and develops the operations of return systems mainly and specifically of beverage packaging including PET plastic bottle, glass bottle, aluminium can and refillable glass bottle. It does not own any operative sections of the return systems, such as reverse vending machines, recycling plants or transport equipment, instead, it oversees and manages these through outsourcing. Its operations are however, monitored by the Pirkanmaa Centre for Economic Development, Transport and the Environment (Pirkanmaa ELY centre). Other beverage package return system administrators also operate in Finland, but PALPA is obviously the largest. The already sorted PET bottles

are mainly transported to Pramia Plastic Oy for treatment, but also to treatment facilities in Sweden and Latvia where they are grinded, washed and pelleted/granulated.

Municipalities are responsible for the collection of all household waste (excluding those covered by PALPA). It collects plastic waste (excluding PVC, at the moment) at public collection points, either in a separate plastic fraction or as a mixed energy fraction through contracted waste management companies such as Lassila & Tikanoja (L&T) Oy. A significant part of their responsibility is also to communicate to household about management of MSW.

Pirkanmaa ELY centre is the supervising authority that monitors all other relevant and necessary authorities, and also gathers statistics and report to Eurostat.

5.5 Data Evaluation

Available data (see *appendix D*) suggest that about 41% of all total MSW in 2015 was recycled, 48% was recovered for energy use while the rest was landfilled (Statistics Finland, 2016). This led to a conclusion that nearly a half of all municipal waste (including separately collected waste, mixed waste and minor other) was burnt for energy recovery in Finland's seven incineration and co-incineration plants.

This underscores the six-fold growth and strength of waste incineration over the past decade. It was however observed that nearly 80% of the separately collected waste (of the 51% of all total MSW) was recycled. According to Statistics Finland (2016), this was reported as taking a substantial stride towards top countries in recycling of separately collected municipal waste.

In the same year 2015, increase in the recycling quantities of electrical and electronic equipment (WEEE), glass and metal waste were achieved. The most influencing factor, however, was reported, as being the specification of the quantity and recycling of fibre (i.e. paperboard and cardboard) packaging waste generated in the field of trade. This made the recycling rate of fibre packaging waste to be substantially high thus bringing Finland closer into an era of complete and rounded circular economy, but not without a substantial increase in plastic waste recycling.

5.6. Case Study Methodology

The performed evaluation in this report is based on data from related and relevant literature reviews from academic journals, textbooks, and internet sources as well as the use of material

flow analysis (MFA). The results in this study are solely based on the studied case analysis tool so developed and nick named ‘PLASTOOL’. Microsoft Excel was chosen and used for ease of analysis and future development of the analysis tool and concept utilized. Different scenarios were examined to determine various possibilities such as enumerated under each scenario.

5.6.1. Case Scenarios

Baseline scenario, S0: This scenario represents the current scenario without any significant form of plastics recycling. In other words, it represents the practice that has been in operation in Finland.

First scenario, S1: This represents separately collected plastics recycling without considerations for mixed residual plastics

- How different is this scenario from S0?

Second scenario, S2: This represents the recycling of the separately collected and mixed residual plastics

- Is this capable of meeting future recycling target such as 2020, 2025 and 2030 targets?
- By how much is the recycling improved compared to S1?
- How much of plastics can be recovered by this means?
- By what percentage can it increase the recycling rate?

Third scenario, S3: This scenario represents recycling the total mixed plastics stream without source separation.

- How different is this scenario from S2?
- Can this be a future scenario with better yield at lesser cost?
- Is it technically, socially and economically sound?
- Can it meet future demands such as high landfill diversion rate?
- What about the purity and quality levels of the recycled products or recyclates?

In the analysis and results that follow in the next chapter, three scenarios were examined separately from a base scenario and compared. The basis of scenarios comparison is based

on three core parameters: targeted plastics source separation efficiency; plastic packaging recycling efficiency; and mixed plastics separation recycling efficiency (table 10 and 11).

The assumed and tested value range for these parameters were taken from credible sources as cited in sections *2.3.2* and *4.7.2*; and modified in this study to correctly predict possible different scenarios using today's technology. As a heuristic approach (typically, different approaches may be possible) this study would like to consider all recycling efficiency values for mixed plastics and plastic packaging as being equal (i.e. same). This assumption is founded on the fact that producing high quality plastic recyclates uses much less recycling time than actual planned time (i.e. lower availability) due to more cleaning and separation steps than low quality recyclates. Consequently, the effects of quality and availability is thus assumed to cancel each other out as performance is assumed or held constant.

The overall plastic packaging and mixed plastics recycling efficiency are also dependent on recycling site engineers' knowledge, professionalism and close collaboration with original equipment manufacturers (OEM).

Table 10: Parameters for comparison basis

	Max.	Min.
Mixed plastic separation recycling efficiency	0,65	0,55
Plastic packaging source separation efficiency	0,60	0,40
Plastic packaging recycling efficiency	0,65	0,55

Table 11: Application of comparison parameters to scenarios

	S0		S1		S2		S3	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Mixed plastics separation recycling efficiency	n/a	n/a	0	0	0,65	0,55	0,65	0,55
Targeted plastics source separation efficiency	n/a	n/a	0,60	0,40	0,60	0,40	0	0
Plastic packaging recycling efficiency	n/a	n/a	0,65	0,55	0,65	0,55	0	0

5.6.2. Estimated Parameters and Assumptions

The estimated Finnish total MSW examined in this study is 2 738 280 tonnes per annum as seen generated in 2015 (see appendix D). Based on this data, source separated amount is 41791 tonnes per annum and the recycled amount is 4778 tonnes per annum. The separately

collected plastic waste is assumed to be a mix of plastic packaging waste and non-packaging small plastic waste.

However, non-packaging small plastic waste are usually left in the mixed waste and sent to energy recovery or landfill. Some non-packaging small plastic items that unintentionally follow plastic packaging waste stream could be subjected to recycling if the polymer type matches with the polymer being sorted in the sorting process.

Available data estimated total plastics content as 13% of the total MSW (see figure 7a). Approximately 80% of this plastics content is assumed to be plastic packaging (Norden, 2014). PET bottles per capital is estimated at 2.5 kg in 2011 and the national objectives for recycling of PET bottles is estimated at 90% in 2015 (Norden, 2014). Targeted plastics source separation is assumed to be kerbside collection with 40-60 % collection efficiency range (Petcore, 2014).

Depending on the efficiency of source separation, the plastic packaging that were not source separated and the remaining 20% total plastics content are assumed to constitute the plastics content in the mixed residual waste. By these assumptions, plastics amount found in mixed residue and source-separated plastics amount would add up completely as total plastic waste amount.

The assumed targeted mixed plastics are PE, PP, PS and PET. These plastics types are typical for packaging; and in accordance with specification and or description (i.e. Fraction-No. 350); this mix should possess a quality or purity rate of at least 90% by mass (Villanueva & Eder, 2014). Assumed availability due to high/extensive cleaning requirements and other unforeseen downtime (including shortstops) events results in an estimated availability value of 65-75%. With the performance accuracy capacity rate of current and emerging sorting technologies averaging at 95% and above; it may be safe to assume a hypothetical separation (and or recycling) efficiency range of 55-65%; as a conservative approach. These assumptions emphasis the need for benchmarking of each component (i.e. performance, quality and availability) of the overall equipment effective of sorting and recycling processes.

5.6.3. Calculations

The adopted recycling rate calculations modality used in this study is based on the input plastics waste to the final recycling process. Consequently, this excludes the weight of the

actual or real recycled plastics output of the final recycling process from the calculations. Subsequently, recycled plastics (following the completion of all necessary separation and or sorting processes) will herewith be distinguished from plastics sent to recycling. See section 5.2 paragraph 7 for further clarification.

With the application of relevant parameters as seen in table 11 to the separation processes involved under each scenario, comes the determination of packaging plastics and total plastics recycling rates with and without the inclusion of PET bottles.

It was considered a safe practice to have an optimistic and pessimistic views of the scenarios under study such that the desired realistic results could be tracked and determined within the optimistic and pessimistic scenes by relevant statistical tools. The statistical tool of choice used in this study is arithmetic means (or averaging method) because of its simplicity and ease of comprehension. Consequently, all analytical results would be and are based on average values derived from combining both optimistic and pessimistic scenes for each and every scenario.

6. RESULTS AND ANALYSIS

The developed hypothetical study case analysis tool has indicated positive and promising possibilities of showing changes (typically increase) not just in the recycling rate of plastic packaging but also in the entire plastic waste recovery. Basing the analysis on currently available data, programs and technologies, it can be demonstrated that the 2020, 2025, 2030 and beyond targets on EU plastic packaging can be reached.

Reaching these goals are however heavily dependent on the performance, quality and availability characteristics of the sorting process and separation technologies that will be deployed with such excellent characteristics such as removal accuracy rate, throughput (ability to cope with volume of plastic waste within specific time), and number range of resin types (i.e. target plastics/polymer types) that can be sorted simultaneously. The latter is key to increasing the separation recycling efficiency of plastics and plastic packaging waste. The quality, homogeneity and volume of sorted plastic waste are largely dependent on the throughput and removal accuracy rate.

6.1. Different Scenarios inclusive of PET bottles analysis and results

Base scenario (S0): This scenario represents the current recycling practice in Finland.

Table 12: Baseline scenario

	Total plastics (ex. PET bottles)	PET bottles
Plastic waste amount [t/a]	355 976	13750
Source separated amount [t/a]	41 791	
Mixed residue amount [t/a]	314 185	
Material recycling amount [t/a]:		
From mixed residue		
From source separated	4 778	
Recycling amount [t/a]	4 778	12375
Recycling rates	1,34 %	90 %
Recycling rate (total plastics, inc. PET)	4,64 %	

Data shown in table 12 indicate a total plastics recycling rate of 1.34% based solely on data provided in appendix E. This figure increases significantly by 3.3% when recycling rate amount from PET bottle is additionally considered. The implications are that, of the 41791 tonnes recovered through source separation for recycling, only 11.4% was recycled, 88.2% recovered for energy purpose and less than 0.5% was landfilled. Even with the inclusion of

PET bottles in the recycling rate calculation, plastic packaging recycling rate would still remain under the 30% mark. A rough estimation suggests a 28.4% ceiling, at the most.

First scenario, S1: This represents recycling separately collected plastics without considerations for mixed residual plastics from MSW

Table 13: Separately collected plastics recycling scenario, an optimistic case

Optimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	213 586	170 869	
Mixed residue amount [t/a]	142 391	113 912	
Material recycling amount [t/a]:			
From mixed residue		0	
From source separated		111 065	
Recycling amount [t/a]		111 065	12375
Recycling rates (packaging)		39 %	90 %
Recycling rate (packaging, inc. PET)		41 %	
Recycling rate (total plastics)	31 %		
Recycling rate (total plastics, inc. PET)	33 %		

Table 14: Separately collected plastics recycling scenario, a pessimistic case

Pessimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	142 391	113 912	
Mixed residue amount [t/a]	213 586	170 869	
Material recycling amount [t/a]:			
From mixed residue		0	
From source separated		62 652	
Recycling amount [t/a]		62 652	12375
Recycling rates (packaging)		22 %	90 %
Recycling rate (packaging, inc. PET)		25 %	
Recycling rate (total plastics)	18 %		
Recycling rate (total plastics, inc. PET)	20 %		

This scenario introduces a distinctive means of viewing and estimating plastic packaging from separately collected plastics which originated from MSW. Even though plastics packaging and non-packaging small plastics from household waste are treated together, the baseline scenario has failed to provide details of this breakdown in S0 as is shown in S1.

As can be deduced from table 13 and 14, the average recycling rate of packaging is 33% and that of total plastics is 27%. Of course, these figures are inclusive of PET bottles as is the practice in Finland. The effect of PET bottles inclusion is a 2 to 3% increase in each case.

Apparently with the present and emerging separation technologies, Finland should be able to reach and surpass the 30% packaging recycling rate without and with the inclusion of PET bottles, as implied by the above results. S1 potent a remarkable recycling rate improvement of nothing less than 20% over S0.

Second scenario, S2: This represents the recycling of the separately collected and mixed residual plastics

Table 15: Separately collected and residual plastics recycling scenario, an optimistic case

Optimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	213 586	170 869	
Mixed residue amount [t/a]	142 391	113 912	
Material recycling amount [t/a]:			
From mixed residue		74 043	
From source separated		111 065	
Recycling amount [t/a]		185 108	12375
Recycling rates (packaging)		65 %	90 %
Recycling rate (packaging, inc. PET)		66 %	
Recycling rate (total plastics)	52 %		
Recycling rate (total plastics, inc. PET)	53 %		

Table 16: Separately collected and residual plastics recycling scenario, a pessimistic case

Pessimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	142 391	113 912	
Mixed residue amount [t/a]	213 586	170 869	
Material recycling amount [t/a]:			
From mixed residue		93 978	
From source separated		62 652	
Recycling amount [t/a]		156 630	12375
Recycling rates (packaging)		55 %	90 %
Recycling rate (packaging, inc. PET)		57 %	
Recycling rate (total plastics)	44 %		
Recycling rate (total plastics, inc. PET)	46 %		

Table 15 and 16 indicate an average recycling rate of 61% and 50% for plastic packaging and total plastics respectively under scenario S2. Additional 28% and 23% recycling rate were achieved in both cases respectively when compared to S1. This represents approximately 85% more in waste plastics being recovered and sent for recycling compared to S1. Overall, this scenario appears to provide a platform to fulfil the 2020 and 2025 plastic

packaging recycling rate targets. In this scenario, the impact of PET bottles inclusion is 1% in plastic packaging and 2% in total plastics. This, unlike in S1, where it is 2% and 3% respectively in both cases.

Third scenario, S3: This represents total mixed plastics recycling without provisions or considerations for separate collection or source separation

Table 17: Total mixed plastic waste recycling scenario without source separation, an optimistic case

Optimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	0	0	
Mixed residue amount [t/a]	355 976	284 781	
Material recycling amount [t/a]:			
From mixed residue		185 108	
From source separated		0	
Recycling amount [t/a]		185 108	12375
Recycling rates (packaging)		65 %	90 %
Recycling rate (packaging, inc. PET)		66 %	
Recycling rate (total plastics)	52 %		
Recycling rate (total plastics, inc. PET)	53 %		

Table 18: Total mixed plastic waste recycling scenario without source separation, a pessimistic case

Pessimistic scene

	Total plastics (ex. PET bottles)	Plastic Packaging	PET bottles
Plastic waste amount [t/a]	355 976	284 781	13750
Source separated amount [t/a]	0	0	
Mixed residue amount [t/a]	355 976	284 781	
Material recycling amount [t/a]:			
From mixed residue		156 630	
From source separated		0	
Recycling amount [t/a]		156 630	12375
Recycling rates (packaging)		55 %	90 %
Recycling rate (packaging, inc. PET)		57 %	
Recycling rate (total plastics)	44 %		
Recycling rate (total plastics, inc. PET)	46 %		

The recycling figures as seen in table 17 and 18 are similar to those from scenario S2. This is expected given the fact that the same amount of waste is to be recovered and sent for recycling. However, the basic differences are in the quality of the recyclates and or final recycled products that would be produced and the amount of yield at a set or planned time.

The yield in S2 is expected to be lower at set or planned time because of the requirement for much cleaning which would most likely lead to very high quality recyclates. The yields of

S3 are expected to be higher with lesser quality recyclates. Apparently, these effects appear to be invisible in the calculations because of the cancelling effect of quality and availability in the determination of the recycling efficiency.

Based upon the above claims, there have been concern about the technologies in used in scenario S3 revolving around the quality of the recyclates being produced. However, with the latest development being witnessed in mixed waste processing facilities using highly automated sorting techniques, utilizing optical based sensors around the world, especially in Europe, one cannot but conclude that this issue is fast becoming trivial.

6.2. Scenarios Comparison and Conclusion without PET bottles

Table 19: Scenarios comparison

	Mixed	Source Separated	Recycling Amount	Packaging Recycling rate	Total plastics Recycling rate
S0	314185	41791	4778	1.82%	1.34%
S1	213586	142391	86858.5	31%	24%
S2	213586	142391	170869	60%	48%
S3	355976	0	170869	60%	48%

Based on the observed multiplicative factor of approximately 1.3 existing between total plastics and plastic packaging recycling rates and the assumption of 40% least source separation of waste plastics from household waste only; it may be possible to draw/sketch and also predict a graphical comparison between plastic packaging and total plastics recycling rates amongst the scenarios as can be seen in figure 28 and 29 using data in table 19.

The 213586 tonnes of plastics waste found in the total MSW residue represents 16.84% (approximately 17%) of the total mixed residual waste as seen in scenarios S1 and S2 in table 19. This figure is closely and practically similar to the 17% reported by JLY in 2015.

The 29% recycling rate increase in plastics packaging observed in scenario S2 when compared to S1 is an indication of significant increase possibilities inherent in recycling rate of plastic packaging from utilizing mixed residual waste from household MSW. This 29-percentage increase is also comparable to the 30% reported by Clausen (2012) in a case with MBT plant combined with advance automated sorting of plastics from residual waste.

The observed leap or changes in recycling rates resulting from S1 to S2 are very significant, as the overall percentage increase are approximately 94% for plastic packaging and 100%

for total plastics. The 100% increase for total plastics can be compared to the 107% more of total plastic sent for recycling when combination of MRF and MWPF were used for the recovery of recyclables and residual waste in GBB's hypothetical study based on the use of new generation MWPF (ACC, 2015).

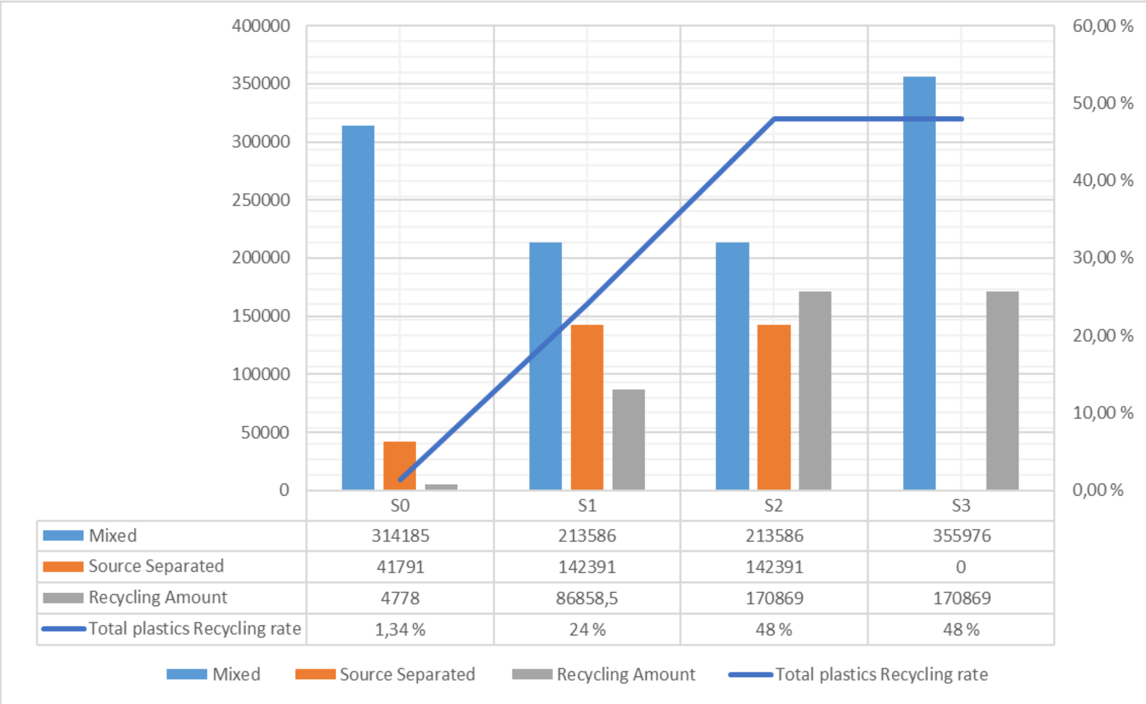
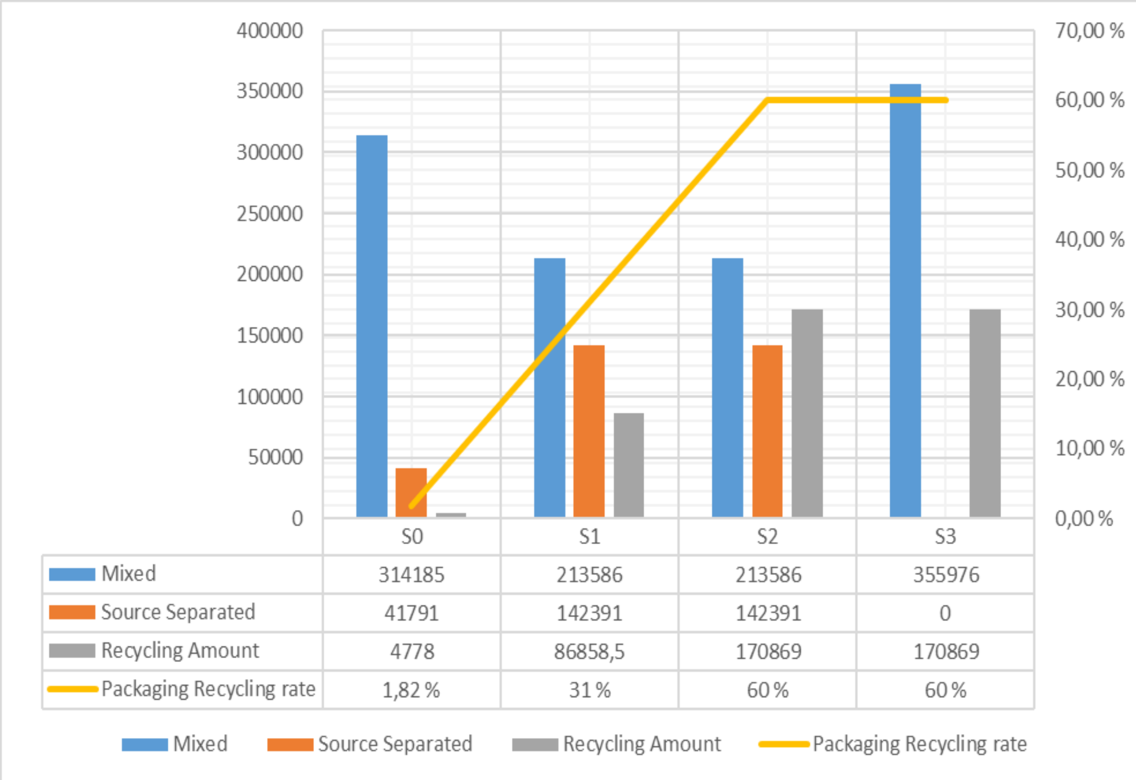


Figure 28: Varying total plastics recycling rate with each scenario

In practice, the resultant recycling rate from S3 is much more in quantity than those portrayed by the rest scenarios involving source separation, that is, S0, S1 and S2. The key reason may be that the overall effectiveness of a first-hand centralized sorting at MWPF is better and greater due to much less wasteful availability than for practices involving source sorting/separation and then further centralized sorting which ostensibly occur at different locations.



	S0	S1	S2	S3
Mixed	314185	213586	213586	355976
Source Separated	41791	142391	142391	0
Recycling Amount	4778	86858,5	170869	170869
Packaging Recycling rate	1,82 %	31 %	60 %	60 %

Figure 29: Varying plastic packaging recycling rate with each scenario

6.3. Discussion

This study had attempted to distinctively pinpoint the dividing line between polymer separation and the final recycling process. Consequently, amount sent for recycling are not necessarily amount recycled. Hence, there exist a clear difference between recycling amount and recycled amount. The analysis and results produced in this report are exclusive to polymer separation/sorting process. With 60% average separation recycling efficiency as derived in this study instance, the hypothetical final recycling process efficiency may be expected to be at least 90% and above such that the actual overall recycling rate may lie between 55-60% (i.e. $55\% < x = 60\%$).

S1 exhibited a phase lift capable of taking the recycling rate of plastic packaging to and beyond the 30% mark. This attainment may be predicted upon renewed interest and commitment to plastic packaging recycling. With such programs, as *"a recycling society"* it may be possible to reach this elusive target in Finland. Note that the inclusion of PET bottles in the recycling rate calculation becomes less and less significant as more and more plastics from household are recovered and sent for recycling.

However, in order for Finland to meet future EU plastics and or plastic packaging recycling targets, S1 appears grossly incapable, given it limitations, constraints and restrictions.

Consequently, with the introduction of S2, there are clear indications that the inclusion of residual waste recycling in Finland have the potential to meet future recycling targets with attendant much higher landfill diversion rate particularly as new generation of mixed waste process facility evolve with perhaps much higher efficiency compared to the one used in this analysis.

At least in theory, S2 and S3 may be seen as having similar recycling rates, but in practice, this may be far from the truth. S2 may lead to more waste due to intensive cleaning of material and perhaps also, the sorting machines, for high quality recyclates. S3 involves less cleaning and perhaps less separation processes compared to S2. This by implication means much more yield at lesser quality. The complete elimination of separately collected scheme and perhaps other separation processes may provide opportunities for significant saving in capital and operational cost.

The pertinent question to ask is that; can S3 represent the future of sustainable waste management with better yield at lesser cost? However, questions still remain as to whether part recycling (as in S2) or full recycling (as in S3) of mixed residual plastics waste is socially acceptable, technically sound, economically justifiable and environmentally friendly. Presently in Europe, options S1 is the most sorted after because of end market requirements and applications requiring near virgin plastics quality. Option S2 and S3 are now in focus for possible increase in plastic packaging recycling rate, with S2 being the most preferred of the two for same reason as mentioned for S1.

While the focus has been on separation technologies performance and recyclate quality; line or process availability may represent the greatest potential for overall recycling efficiency improvement. This is especially so, since unexpected shortstop failures per week or month may represent the biggest issue that brings down the performance of most automated sorting lines or processes. Consequently, a real-time monitoring for fast recognition and response to these stoppages may help provide the much-needed improvement.

7. RECOMMENDATION

First and foremost, I acknowledge the fact that the demonstrated case study and it outcomes are hypothetical and may not represent the true state of things and further admit the possibility of human error in judgement. Hence, I strongly recommend that the outcomes of this study case about Finland in this report be thoroughly examined and compared with relevant industry or authority figures or outcomes from the past, the present and projected future, which probably may be a non-disclosure matter. Not until it is considered relevant should the outcomes of this study be considered for implementation. And when this is the case, I further recommend the following by way of suggestions.

7.1 Suggestion

- Enhance policy-based act or decree that support the recovery and recycling of waste fractions from mixed MSW within Finland
- Conduct further research to establish facts and clear possible ambiguity over grey areas. In other words, feasibility study on this topic may be necessary
- Start a pilot program at a desired localized region for prove of concept
- Encourage plastic packaging and non-packaging plastic waste recycling and invest in the relevant modern day and emerging polymer waste separation technologies
- Build new MBT facilities or retrofit existing SRF plants ready for mixed waste sorting
- Consider cutting down on material recovery for fuel
- Start a campaign for total plastic recycling not just plastic packaging waste only
- Start aggressive total plastic recycling to prevent micro plastics from entering food chain
- Single stream and MBT should be seriously considered, research and possibly implemented at some to determine it potential and prospect
- Attempts to combine different sorting and collection strategies should be considered and evaluated
- Landfill only Target (LoT) for total plastic waste should be considered and appraised
- Unlocking hidden potentials towards a zero-waste future may just be lurking around and an era when waste is seen as wealth may just be around the corner, so get involved

7.2. Proposal

I am proposing LoT (Landfill-only-Target). The reason and idea behind this proposal are:

- This will tend to promote and support some of the finest ideas, schemes and programs in the waste management industry/world such as landfill ban and zero waste. Both can be achieved when LoT is set to zero.
- When LoT is set, it becomes the reference and other target and/or rates achieved at the different higher level of hierarchy becomes indicative of the progress made so far. At best, they become complementary targets.
- With the reduction and/or elimination of all kinds of waste fractions going to landfill being the central goal at the heart of waste management industry; having LoT makes lots of sense and directly relevant.
- LoT could serve as the basis and/or the starting point for planning, policy and decision making with regards to specific waste material fractions such as organic waste (existing in the EU) and inorganic waste (yet to exist).
- It could help eliminate multiple targets thus save time, space and resources planning targets at the higher levels of hierarchy. In other words, setting target at other levels may become unnecessary.
- LoT provides a sense of bottom-to-top approach in the waste management hierarchy.
- LoT can help countries known/determine which waste management scheme, strategy and methodology are not working or performing to expectation by their output/outcome.
- LoT could lead to the harmonization of waste management methodologies.
- Complacency and refusal by countries to push beyond the current waste management achievements can easily be expose and overcome.
- LoT can be flexible and specific, that is, in terms of target value setting for different wastes material fractions.
- It could help identify and focus more on the waste material fractions that are ‘troublesome’ (i.e. hard to prevent from being landfilled)
- Lastly, LoT could promote innovations at the different levels of the waste management hierarchy.

8. CONCLUSION

This study has been able to identify the major contributing factors amongst many factors responsible for the low rate of plastic wastes recovery and recycling, as: low weight-to-volume ratio problem, existence of plastics (often visibly indistinguishable) having different and distinct properties and the lag in technology to bring about the complete separation of these plastics types often found mixed, in mixed waste, such as household waste and other sources of MSW.

The emergence of new plastics separation technologies and or combination of existing and emerging ones are now playing important role in accurately identifying, sorting and increasing the recovery and recycling rate of plastics through high separation accuracy performance and high yield. The understudied case had shown that it is possible to gain or increase plastic packaging recycling rate by an average of 29 from household residual waste. This represents the recovery of an approximate average of 48% (nearly half) of plastic packaging materials found in mixed residual waste from households.

Although recycling is often a choice waste management option over waste incineration for environmental reason. However, this study identified economic reason as the overarching mandate behind plastics recycling. In other words, quality recycling is at odd with quantity recycling. Quality recycling of plastics will be in favour of the economy, whereas quantity recycling will be in support of the environment. Key stakeholders and policy makers in the society are left to decide which is more beneficial for the general good. Just as their involvement and participation are important in making plastics recycling happen, so also are their decisions in the final products' impacts.

Further research into the topic of this report could be a possible micro-level view evaluation of each targeted resin types under the packaging and non-packaging categories; instead of evaluating all targeted resin types as one mix (i.e. macro view) under each category. This, I pre-assume would be able to provide a more balanced, accurate and true representation of expected outcomes. Furthermore, a thorough work on the optimization of waste plastics value chain system and or process may afford us the opportunity to significantly further increase waste plastics recycling rate. Beyond these, I would further recommend a thorough study into "the final recycling process" and cost-benefit of collection, identification, sorting and reprocessing of plastics waste from mixed waste with and without source separation.

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APPENDICES

Appendix A: Finnish C&D waste composition

Amounts of C&D waste	Approximately 23 million tonnes (including excavation waste) to which must be added 410,000 tonnes of hazardous waste (Statistics of the Technical Research Centre of Finland, 2006) 1.6 Mt from house building sites (2007): renovation (57%), demolition (27%), and new building sites (16%)	
Waste factors	New construction	1 to 17 kg/r-m^3
	Small renovation	5 to 15 kg/r- m^3
	Middle Size renovations	50 kg/r- m^3
	Full-size renovation	200 kg/r- m^3
	Hazardous waste	2 g/ kg/r- m^3
Material composition of the C&D waste stream	Wood	40%
	Mineral	31%
	Metal	14%
	Others	15%
And of life options and rates	**Construction waste** - Material recovery - Energy recovery - Landfilling	 33% 27% 40%
	Recovery from **demolition waste**	50%
Analysis of the current state	Low material recovery rate; high energy recovery due to the important share of wood waste.	
Towards the 70% target	The National Waste Plan for 2016 sets a 70% target for recycling, re-use and recovery of C&D waste, including energy recovery. Aim for 2016: replace 5% of all gravel and crushed stone used in earthworks (3 to 4 Mt) by C&D waste. By 2016, new construction will probably be replaced by renovation activities. **Main challenges towards reaching the target**: - the calculation of the statistics on re-use and recovery of C&D waste is not currently reliable, the update of building coefficient not being frequent enough - the number of wooden buildings in Finland and the difficulty of recovery and re-use of construction wood waste	

Appendix B: Finnish packaging recycling rate between 1998 and 2014 (RINKI, 2016)

Recycling rate (target)

Year	Total	Fiber	Glass	Metal	Plastic	Wood
1998	45 (42)	57 (53)	62 (48)	16 (25)	10 (15)	
1999	50 (42)	61 (53)	78 (48)	19 (25)	13 (15)	
2000	50 (42)	62 (53)	64 (48)	25 (25)	14 (15)	
2001	47 (42)	58 (53)	50 (48)	39 (25)	15 (15)	
2002	49 (55)	61 (60)	50 (60)	46 (50)	15 (22,5)	
2003	41 (55)	63 (60)	61 (60)	50 (50)	14 (22,5)	7 (15)
2004	40 (55)	70 (60)	55 (60)	55 (50)	15 (22,5)	7 (15)
2005	43 (55)	79 (60)	63 (60)	54 (50)	14 (22,5)	5 (15)
2006	49 (55)	86 (60)	74 (60)	59 (50)	16 (22,5)	8 (15)
2007	52 (55)	88 (60)	81 (60)	70 (50)	18 (22,5)	10 (15)
2008	57 (55)	93 (60)	80 (60)	75 (50)	23 (22,5)	20 (15)
2009	55 (55)	95 (60)	45 (60)	84 (50)	25 (22,5)	21 (15)
2010	56 (55)	96 (60)	61 (60)	80 (50)	26 (22,5)	18 (15)
2011	59 (55)	97 (60)	97 (60)	82 (50)	25 (22,5)	18 (15)
2012	59 (55)	99 (60)	78 (60)	85 (50)	25 (22,5)	17 (15)
2013	58 (55)	98 (60)	77 (60)	82 (50)	23 (22,5)	15 (15)
2014	57 (55)	101 (60)	81 (60)	82 (50)	25 (22,5)	13 (15)

Appendix C: Whole plastic containers, and flake and size-reduced optical sortation technologies (ACC, 2011)

Whole Unit: Singulated Feed

	Rofin Australia Pty Ldt.	**Green Machine**
Criteria	**Rapid Sort 75**	**GreenEye**
Basis of technology	NIR and visible spectroscopy	Proprietary, patent pending
Primary application	Separating comingled and contaminated single-resin streams	Sort bottles by resin or color
Plastics identified	PET, PE, PVC, PP, PS, and others as required	Identification of all grades of plastics
Sorts non-bottle rigids in addition to bottles	Yes	
Colors sorted	Clear PET, colored PET, natural PE, colored PE, and other colors as required	Yes
Throughput (average)	Up to 5 bottles per second (equivalent to 1800 lbs./hour) per line	12,000 lbs/hour with 60" belt width
Accuracy	>99,0% (>99.8% of PVC from PET, >99.8% removal of PP from PE)	95% +

Whole Unit: Mass Feed

	MSS		Pellenc		
Criteria	**Aladdin**	**Sapphire**	**Mistral**	**Sirocco**	**Bi-Techno**
Basis of technology	NIR + Color	NIR	NIR	Vision Technology (color)	NIR and Vision technology (color)
Primary application	Obtaining pure streams of PET and HDPE	Obtaining pure streams of PET and HDPE	Obtaining pure streams of PET and HDPE	Color sort for PET or HDPE	Obtaining pure streams of PET
Plastics identified	All resins (PET, PE, PVC, PP, PS, PLA, etc.)	All resins (PET, PE, PVC, PP, PS, PLA, etc.)	PET, PVC, PS, EPS, HDPE, Beverage carton, PP, PE, PLA	N/A	PET, PVC, PS, EPS, HDPE, Beverage carton, PP, PE, PLA
Colors sorted	All colors	No	No	PET: Tri-sort into clear, green, and "other" OR blue, mixed, crystal HDPE: Natural and colored	PET: Tri-sort into clear, green, and "other" OR blue, mixed, crystal HDPE: Natural and colored
Sorts non-bottle rigids in addition to bottles	Yes	Yes	Yes	No	Yes
Throughput (average)	Up to 6 tons/hr for plastic bottles/containers	Up to 6 tons/hr for plastic bottles/containers	13,000 lbs/hour	13,000 lbs/hour	13,000 lbs/hour
Accuracy	92% - 98%	92% - 98%	< 50 ppm of PVC and metal contaminants		98%
Upgrades	All-Metal Detector, Split machine	All-Metal Detector, Split machine	Metal detector unit	Metal detector unit	Metal detector unit

Whole Unit: Mass Feed (continued)

	TITECH	EagleVizion	Visys	Best
Criteria	**Autosort**	**Aquilla Series**	**Cayman**	**NIREX**
Basis of technology	NIR and spectroscopy color detection(also available in just NIR)	NIR	NIR	NIR and vision techknology
Primary application	Obtaining pure streams of material from mixed resins	Obtain pure streams of HDPE and PET	Obtain pure resin streams from mixed plastics or wastes	Obtaining a pure resin stream from mixed plastics
Plastics identified	PET, PETG, HDPE, LDPE, PP, PVC, PLA, PS, HIPS, ABS, PC, PC-ABS, POM, PA, PPO, PMMA	HDPE (color vs natural), PP, PET, PS, PVC, Tetra, PLA, etc.	PET, HDLPE, PP, PS, PE, PVC and others	PET, HDPE, PE, PP, PVC, and others
Colors sorted	All colors	Yes	No	Yes
Sorts non-bottle rigids in addition to bottles	Yes	Yes	Yes	Yes
Throughput (average)	Up to 10 tons/hour	1 to 8 tons/hour (depends on inbound)	On average up to 5 tons/ hour depending on input and unit width	4 tons/hour
Accuracy	99.99% when using multiple machines	90%	Up to 99% depending on the input	Depends on the product
Upgrades		Can be combined with several belts		Can be combined with other sorting units into one tower.

Whole unit: Mass feed (continued)

	NRT				S+S	
Criteria	**MultiSort ES**	**MultiSort IR**	**SpydIR**	**VinylCycle**	**Varisort CS-P**	**Varisort NS-P**
Basis of technology	Vision based	NIR	NIR	X-ray	CCD Linear camera	NIR
Primary application	Often used for color sorting PET bottles	Purifying PET, or removing a selected resin from co-mingle	Remove selected polymers from a mixed stream	Remove PVC from PET	Purify PET streams by color	Separate mixed resin streams
Plastics identified	None	PET, HDPE, PP, PVC, PLA, PE, PS	PET, HDPE, PP, PVC, PLA, PE, PS	PVC, PET	No	HDPE, PE, PET
Colors sorted	All colors	No	No	No	All	n/a
Sorts non-bottle rigids in addition to bottles	Yes	Yes	Yes	Yes	Yes	Yes
Throughput (average)	5 metric tons/hour	5 metric tons/hour	5 metric tons/hour	3 metric tons/hour	From 1000 lbs/hour to 20,000 lbs/ hour depending on how the unit is scaled	
Accuracy	95%	99%	99%	99%	Ranges from 90% to 99.8% depending on input	
Upgrades	ColorPlus, MetalDirector	MetalDirector	MetalDirector		Different ejector modules available, up to 320 independently working air ejectors. Sensor modules can be combined in one machine, sensors including metal detector upgrade, 2- or 3- way sorting possible, Visutec Online Quality control	

Whole Unit: Mass Feed (continued)

	Eveready Manufacturing	BT-Wolfgang Binder GmbH		
Criteria	**NIRSort**	**REDWAVE NIR/C Reflection**	**REDWAVE NIR Transmission**	**REDWAVE C**
Basis of technology	NIR and vision spectroscopy	NIR Spectroscopy Color detection	NIR Spectroscopy	Vision spectroscopy with CCD Camera
Primary application	Sort mixed streams of bottles	Separation of opaque, transparent and translucent plastics (beverage containers, rigids and films)	Separation of highly transparent and translucent plastics (films, multi-layer materials)	Separation of plastics by color
Plastics identified	PP, PVC, PE, ABS, PMMA, POM, PC, PC/ABS, PS, and others	PET, PE, PP, PS, PVC, ABS, PC, POM, PU (and all other non-black plastics)	Any thin multi-layer plastic, such as PE with PVC	No
Colors sorted	Yes	Yes	No	Yes
Sorts non-bottle rigids in addition to bottles	Yes	Yes	Yes	Yes
Throughput	2,000 – 4,000 tonnes/hour	Depends on the sorting width and the input material	Depends on the sorting width and the input material	Depends on the sorting width and the input material
Accuracy	99%	Up to 99%, depending on the input material	Up to 99%, depending on the input material	Up to 99%, depending on the input material
Upgrades		REDWAVE NIR/C Reflection	REDWAVE NIR Transmission	REDWAVE C

Whole Unit: Mass Feed (continued)

	RTT Steinert GmbH					
Criteria	**UniSort C**	**UniSort P**	**UniSort PX**	**UniSort Multi5**	**UniSort P4000**	**UniSort RDF**
Basis of technology	Color sensors (Linear cameras)	NIR	NIR	NIR	NIR	NIR
Primary application	Separate PET bottles by color	Sort mixed containers (two sort)	Sort mixed containers (three sort)	Sorts mixed bottles (five sort)	Refuse derived fuel processing	Remove PVC from Refuse derived fuel
Plastics identified	No	PET, HDPE, PP, PS, PVC, tetrapak	PET, HDPE, PP, PS, PVC, tetrapak	PET, HDPE, PP, PS, PVC, and others	PVC, PE, PET, PP, PS and others including tetrapak and film	PVC
Colors sorted	Yes	No	No	Yes	No	No
Sorts non-bottle rigids in addition to bottles						
Throughput	1.5-4 tons/hour depending on sorting width	Depends on sorting width (3 meters/second)	Depends on sorting width (3 meters/second)		2.5-4.0 tons/hour	Depends on material
Accuracy	97%	90% or better	90% or better	80-98%	80-98%	90% in positive sorting
Upgrades						Available in split version

Flake and size-reduced sorting technology

	Buhler	Pellenc	Rhewum	Unisensor
Criteria	**Sortex Z+ series**	**Mistral + Metal Sensor**	**DataSort**	**PowerSort 200**
Basis of technology	Vision-based and high-resolution infrared sensors	High resolution NIR and Vision technology (color)	CCD camera system, lighting by LED light bars available in various colors, depending on colors to be sorted (e.g. in red for sorting of red/orange/yellow/brown particles)	Ultra-High-Speed Laser Spectroscopy
Primary application	Color sort PET flakes, PVC flakes, pellets, nylon	Shredded e-scrap	Separating particles by color	Producing a high-quality product stream for applications such as bottle-to-bottle recycling
Plastics identified	No	Engineering-grade resins, including: ABS, HIPS, PC, PC-ABS, PP, PU, PMMA	All kinds of plastics, e.g. PET, PE, PP, PS, PVC…	All resins, including: PET, PVC, Nylon, Silicone, PLA and barrier layer material
Colors sorted	Yes – sees all shades of colors	Segregation of black plastics	All colors, only have to be different enough (camera is not able to see more see more than mens eye)	All colors, including black plastic
Throughput	1350 lbs/hour to 2315 lbs/hour depending on model	13,000 lbs/hour	4.0 to 7.5 metric tons/hour	up to 3 tons per hour
Accuracy	99.9% or higher	Metal detector unit	Up to 97%	98% or higher
Upgrades		Mistral + Metal Sensor		

Flake and size-reduced sorting technology (continued)

	S+S			EagleVizion	
Criteria	**Flake Purifier N**	**Flake Purifier C**	**Varisort X**	**Flake Sorter & Large shred Plastics**	**E-plastics sorter**
Basis of technology	NIR	CCD linear camera	X-ray	NIR	NIR
Primary application	Purify resin streams, identifying e-plastics	Color sorting	Identifying BFR-containing plastics	Obtain pure stream of PET or HDPE	Sort shredded plastics from electronics
Plastics identified	PET, HDPE, PLA, PVC, and more	No	BFR- and chloride-containing plastics	PE colored, PE natural, PET, PVC, PS and others	ABS, PS, PP, PA, PVC, PE, PET, PBT, PUR, PC, PMMA, PC+ABS, ABS+PVC, PPE+SB
Colors sorted	No	Yes	No	No	No
Throughput	From 1000 lbs/hour to 20,000 lbs/ hour depending on how the unit is scaled		1,000 lbs./hour to 5,000 lbs./hour	In qualifying phase	In qualifying phase
Accuracy	Ranges from 90% to 99.8% depending on input		Depends on FR content	In qualifying phase	In qualifying phase
Upgrades	Different ejector modules available, up to 320 independently working air ejectors. Sensor modules can be combined into one machine. Metal detector upgrade available.		None	Duel Ejection	Duel Ejection

Flake and size-reduced sorting technology (continued)

	Satake				
Criteria	**Scanmaster IE**	**MikroSort AF**	**ScanMaster XE**	**RGB Full Color Belt Sorter**	**PelletScan**
Basis of technology	High resolution CCD Camera	CCD Linear cameras	Proprietary InGas/Color camera technology	Full Color Cameras (RGB)	High-res CCD cameras
Primary application	Color separations (green and other colors from clear, brown from green, toasted PVC from PET)	Sorting PET flake by color	Removing clear PVC from PET, and other non-plastic contaminants	Color separation (green and other colors from clear, brown from green, toasted PVC from PET)	Used for sorting pelletized flake (looking for black specks)
Plastics identified	PET, Toasted PVC	None	PET, PVC, PLA, EBOH and other low-melts	PET, Toasted PVC	No
Color sorted	Yes	All, including slight color differences (e.g. blue, light blue and light green)	No	Yes	Yes (color sort only)
Throughput	500-10,000 Lbs/Hr	1-3 tons/hour	500-10,000 Lbs/Hr	Up to 6,000 lbs/hour	2,000 – 5,000 lbs/hour
Accuracy	Up to 99%		70% - 95% +, depending on particle size, contamination levels and other variables	Up to 99%	Up to 99%
Upgrades	Toll workers kit, Satake Everywhere remote monitoring, DataScan				DataScan

Flake and size-reduced sorting technology (continued)

	BT-Wolfgang Binder GmbH	Innov-X & BT-Wolfgang Binder	RTT Steinert GmbH	Mogensen
Criteria	REDWAVE XRF Plastics	Redwave QXR	UniSort PM	MikroSort AF
Basis of technology	X-Ray Fluorescence	XRF	NIR	CCD Linear cameras
Primary application	Separation of flame retarded plastics and Chlorides	Purify PET and WEEE streams Purify Auto Shredder Residue	Removal of PVC and metal from shredded scrap	Sorting PET flake by color
Plastics identified	BFR and chloride-containing plastics	Can remove black PVC and BFR containing plastic	PVC	None
Colors sorted	No	No	No	All, including slight color differences (e.g. blue, light blue and light green)
Throughput	Depends on the sorting width and the input material	- *	2.5 to 8.0 tons/hour	1-3 tons/hour
Accuracy	Up to 99%, depending on the input material	- *	80%	
Upgrades				

* System is currently being developed, using proven XRF technology. Expected market release is Q3 2010.

Flake and size-reduced sorting technology (continued)

	Visys			MSS	
Criteria	**Spyder**	**Python**	**Tyrex**	**E-Sort**	**L-VIS**
Basis of technology	Lasers	Lasers and cameras	X-ray	NIR, Color and metal sorting	High resolution color camera
Primary application	Separation of plastics based on structure or color differences	Sortation of various streams based on color, structure or shape differences	Density separation in applications such as ASR, WEEE and plastics	Sorts shredded plastics from electronics	Color separating flake, pellets and e-scrap
Plastics identified	No	No	BFR and chloride containing plastics	All resins, including: ABS, HIPS, PC, PC-ABS, etc.	n/a
Colors sorted	Yes	Yes	No	All Colors	All Colors
Throughput	1 – 3 Tons/hour	1 – 3 Tons/hour	1 Ton/hour	Up to 6,000 lbs/hr	Up to 8,000 lbs/hr
Accuracy	Up to 99% depending on the input	Up to 99% depending on the input	Up to 99% depending on the input	92% - 98%	93% - 99%

Flake and size-reduced sorting technology (continued)

	Best			
Criteria	**Ixus**	**Genius**	**Helius**	**NIREX**
Basis of technology	X-ray	High-res CCD cameras, lasers (including NIR, UV, LED or fluorescent lighting)	Lasers	NIR and vision techknology
Primary application	Shredded e-scrap	Purifying a selected stream, removing color contaminants	Purifying a selected stream, Removing color contaminants	Obtaining a pure resin stream from mixed plastics
Plastics identified	BFR- and chloride-containing plastics	PET, HDEP, PE, PP, PC, PVC and others	PET, PVC, others	PET, HDPE, PE, PP, PVC, and others
Colors sorted	No	Yes	Yes	Yes
Throughput	1 ton/hour	2 tons/hour	1.5 tons/hour	4 tons/hour
Accuracy	Depends on product	Depends on product	Depends on product	Depends on the product
Upgrades	Cameras and lasers can be added depending on the application			Can be combined with other sorting units into one tower.

Appendix D: Finnish plastic packaging identification

PLASTIC PACKAGING

YES

Empty, clean and dry plastic household packaging

- Plastic food packaging such as yoghurt pots, butter tubs and packaging for colt cuts, cheese and ready meal
- Detergent, shampoo and soap packaging
- Plastic bottles, cans and jars, preferably flattened
- Plastic carrier bags, bags and wrappings

NO

- Dirty plastic packaging and mixed waste
- PVC packaging
- Other plastic products or plastic packaging waste from firms

03 PVC

Any packaging that contains residues of dangerous substances and pressurised packaging (e.g. paint, chemicals, oils, medicines, hairspray) must be taken to your local hazardous waste collection point.

RINKI

Thank you for sorting!
Finnish Packaging Recycling RINKI Ltd • www.rinkiin.fi/sorting-instructions

Appendix E: Finnish waste treatment in 2015 (in tonnes) (Statistics Finland, 2016)

Waste	Amount	Recycling	Energy recovery	Landfilled
Mixed waste total	**1 268 259**	**553**	**975 358**	**292 348**
Separately collected waste total, of which	1 391 044	1 092 036	290 267	8 741
Paper and board waste	516 491	479 302	37 180	9
Organic waste	364 602	341 247	20 639	2 716
Glass waste	84 815	76 975	7 672	168
Metal waste	114 382	114 382	0	0
Wood waste	36 917	3 262	33 655	0
Plastic waste	41 791	4 778	36 845	168
Electrical and electronic scrap	63 603	63 603	0	0
Other separately collected waste	168 444	8 487	154 277	5 680
Other	78 976	18 749	46 554	13 673
All total	**2 738 280**	**1 111 338**	**1 312 180**	**314 762**

Source: Waste statistics 2015, Statistics Finland

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